Cognitive Readiness – Training for Non-Routine Control-Room Situations
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Ruhr-University Bochum, Germany

27.-28. April 2016
Human Factors in Control
Human Factors in Operational Risk Management
Focus on Barrier Management
About the coming 45 min...

- Cognitive readiness: An introduction
- Training outcomes as safety barriers
- The challenging conditions for task work and team work skill execution
- Training science principles for task work & team work skill acquisition to become cognitive ready
- Training design für cognitive readiness: The „Staged Process Control Readiness Training“
- Maintaining cognitive readiness through refresher interventions
- Take home message
Cognitive readiness: An introduction
„Inert knowledge is the opposite of cognitive readiness to perform under stressful conditions“
Cognitive readiness – training for non-routine control-room situations

**General** challenges in training

- Training methods/duration/frequency (do not) match learning objectives
- (no) Positive transfer
- (stress/time pressure) Conditions of performance not considered

Diagram:

- **Training** → **KSAs at the end of training** → **Performance on the job**
  - Routine
  - Non routine/normal
Cognitive readiness – training for non-routine control-room situations

- Training = „A planned and systematic effort to modify or develop knowledge/skill/attitude (KSAs) through learning experience, to achieve effective performance in an activity or range of activities

  - It’s purpose in the work situation is to enable an individual to acquire abilities in order to that he or she can perform adequately a given task or job“ (Buckley & Caple, 2008, p. 5)

- Positive transfer of training: The extend to which the learning that results from training experience transfers to the job and leads to meaningful changes in work performance (Baldwin, Ford & Blume, 2009)
Cognitive readiness – training for non-routine control-room situations

The challenge for training design in HROs

- **Threat**: Training methods/duration/frequency (do not) match learning objectives
- **Threat**: (no) Positive transfer
- **Threat**: (stress/time pressure) Conditions of performance not considered

- **Training**
  - Learning objectives do not consider performance conditions:
    - Information overload and intransparency
    - Task overload
    - Peer/Supervisor pressure
    - Coping with physiological reaction

- **Cognitive readiness**
  - Skill decay due to long periods of non-use

- **Performance on the job**
  - Routine
  - Non routine/normal
  - Non routine/abnormal

→ HF/Human Error
Cognitive readiness

Cognitive readiness (CR) is possessing the

→ **Action-oriented competencies** (experienced knowledge, skills and attitudes, KSAs) that individuals and team members need to establish and sustain competent professional performance in the **dynamic, complex, and unpredictable environments** (...) (Kluge & Burkolter, 2013; Bolstad, Cuevas, Costello, & Babbitt, 2008, p. 970; adapted from Morrison & Fletcher, 2002)

Cognitive readiness = Optimization and enhancement of human cognitive performance (→ action) which is critical for effective performance, especially

– for performing multiple functions and
– for adaptation to **dynamic threats** (Fatkin & Patton, 2008)
– and non-routine situations
Cognitive readiness for process control means...

**Couplings and interconnections** require the operator to simultaneously process the interplay of cross-coupled variables in order to either assess a process state or predict the dynamic evolution of the plant.

**Dynamic effects** require the operator to mentally process and envisage the change rates of cross-coupled variables and to develop sensitivity for the right timing of decisions in order to be successful.

**Non-transparency** requires the operator to work with more or less abstract visual cues that need to be composed into a mental representation and need to be compared with the operator’s mental model.

Cognitive readiness for process control means...

Multiple or conflicting goals require the operators either to balance management intentions or to decide on priorities in case of goal conflicts in the decision making process, e.g. which course of actions to take.

Comprehension of MPC and RTO philosophies and making sure that CROPs understand the advanced control and optimization philosophies that are at the basis of MPC and RTO, since they have to validate the proposed results before accepting/rejecting their implementation in the on-line control strategy model predictive control (MPC)/ real-time optimization (RTO).

Crew coordination complexity incorporates small crews, e.g., CROPs, FOPs and supervisors, who are responsible for overall system operations and calls for the operators to concurrently interact with team members in order to orchestrate individual actions into a coordinated flow of actions to either assess the situation or choose a course of actions.

Cognitive readiness training in process control

- It is called “readiness training” because it prepares operators for the non-routine situations.
- As a large proportion of the training objectives and performance are not routinely called upon every day, the training should foster the readiness for controlling complex systems and also prepare for non-routine situations.
- Readiness is defined as possessing the task work and team work knowledge and skills an operator needs to establish and sustain competent performance in order to be in control in routine, non-routine/normal and non-routine/abnormal situations.
Training is **not** the barrier – it’s the training outcome!

Training is useless if it does not support the acquisition of skills that are needed and applied in hazardous situations!
Training outcomes as safety barriers
Training **outcomes** as safety barriers

„Safety Barriers are physical and/or non-physical means planned to prevent, control, or mitigate undesired events or accidents“ (Sklet, 2006)

Generic safety functions related to a process mode (Sklet, 2006, p. 498)
Training **outcomes** as safety barriers

**Cognitive Readiness (CR) is a training outcome:** The **action-oriented competencies** (experienced knowledge, skills and attitudes, KSAs) that individuals and team members need to establish and sustain competent professional performance in the **dynamic, complex, and unpredictable environments (…)”**

**planned to prevent, control, or mitigate undesired events or accidents”**

![Diagram](image)

**Generic safety functions related to a process mode** (Sklet, 2006, p. 498)

Training outcomes as safety barriers

“(…)a hazardous event can be prevented by a set of proactive barrier functions and mitigated by a set of reactive barriers functions” (Johansen & Rausand, 2015. p. 50)

Training **outcomes** as safety barriers

“(…) a hazardous event can be prevented by a set of proactive barrier functions and mitigated by a set of reactive barrier functions” (Johansen & Rausand, 2015, p. 50)

Training outcomes as safety barriers

“(...) distinction between hardware and behavioural barriers and their related management delivery systems is made (...)“  (Guldenmund et al., 2006)

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<th>Behavior Related Systems</th>
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<td>- Procedures, plans, rules &amp; goals</td>
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<td>- Availability, manpower-planning</td>
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<td>- Inspection, testing, performance monitoring, maintenance &amp; repair</td>
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Training **outcomes** as safety barriers

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The challenging conditions for task work and team work skill execution
Cognitive readiness – training for non-routine control-room situations

The challenge for training design in HROs

- Training methods/duration/frequency (do not) match learning objectives
- (no) Positive transfer
- (stress/time pressure) Conditions of performance not considered
- Routine
  - Non routine/normal
  - Non routine/abnormal

Learning objectives do not consider performance conditions:
- Information overload and intransparency
- Task overload
- Peer/Supervisor pressure
- Coping with physiological reaction

Skill decay due to long periods of non-use

HF/Human Error
Cognitive readiness – training for non-routine control-room situations

Where is cognitive readiness needed?
When performance needs to be applied
... under time pressure
... in a personally threatening and
... in intransparent & dynamically changing situations

„Safety barriers are physical and/or non-physical means planned to prevent, control, or mitigate undesired events or accidents“ (Sklet, 2006)
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Cognitive readiness: refresher interventions

- Routine
  - Standard Operating Procedures (SOPs)
    - Rule-based behaviour
- Abnormal
  - No Standard Operating Procedures (SOPs)
    - Knowledge-based behaviour

Performance in Process Control

Critical thinking and decision training
Skill acquisition for cognitive readiness

Skill acquisition includes:
− Learning AND Performance of these skills
− Skill Execution under challenging conditions

Challenging conditions are situations which....

<table>
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| **Routine situations** | - Require routine control and regulation of the process  
- Based on rule-based behaviour  
- The situation is well handled by Standard Operating Procedures (SOPs)  
- E.g. “daily business”, plant monitoring and control |
| **Non-routine/normal situations** | - Require drawing on skills which have not been used for a longer period of time  
- Rule-based behaviour  
- The situation is well handled by Standard Operating Procedures (SOPs)  
- E.g. “exceptional business”, fault repair or start-up of plant, but is still rule-based behaviour |
| **Non-routine/abnormal situations** | - Require problem-solving skills and knowledge-based behaviour  
- Situation is a) ambiguous and includes b) unanticipated major c) threats to system survival coupled with d) limited time to respond  
- E.g. low-probability, high-impact situation, an explosion in a subunit of the plant caused by a safety-related rule violation or natural disasters such as earthquakes, tsunami |
Cognitive readiness for non-routine/normal situations

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Skill acquisition for cognitive readiness

Task work requirements for non routine/abnormal situations

1. Interpret warnings and indicators
2. Communicate observations to crew members
3. Select the correct SOP
4. Execute SOP (fixed, contingent, parallel, free)
5. Monitor whether the system stays in predefined limits and range
6. Check whether system reacts in the intended direction and the problem is solved
Skill acquisition for cognitive readiness

Team work requirements for non routine/abnormal situations

Perceiving the difference between normal and abnormal
- Collecting and restructuring of data
- Combine, sort & filter cues
- Searching for patterns
- Detecting patterns of cues
- Sharing mental models
- Exchanging hypotheses about causes of problems

Orchestrating actions
- Execute SOP (fixed, contingent, parallel & free) correctly

Selecting course of action

Monitor goal achievement

Intention

Action

Events

Carrying out action

Assessing situation

Choosing what to do

Time pressure

Disturbance/Interference

Alarms
Training science principles for task work & team work skill acquisition to become cognitive ready
Skill acquisition for cognitive readiness

Main question: How do we transform a novice into an expert who is able to execute skill under high workload?

<table>
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<th>Definition</th>
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<td>Novice</td>
<td>Someone who is new and has had some minimal exposure to the domain</td>
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<tr>
<td>Expert</td>
<td>Someone whose judgments are uncommonly accurate and reliable, whose performance shows consummate skill and economy of effort, and who can manage effectively with rare and difficult cases and has special skills or knowledge derived from extensive work experience also with sub-domains</td>
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– The overall learning requirements include the development from a novice to an expert.
– The learning process implies the **accumulation of instances** through work experience and practice.
– Instances are stored in the **episodic memory**

Skill acquisition for
cognitive readiness
Episodic memory? What is that for?

- Involves **re-experiencing a past event** that is specific in time and place
- Represents "short time slices of experience”
- Is close to experience, predominantly represented in the form of images, has an observer’s perspective and contains sensory-perceptual-conceptual-affective summary features of that experience
- Is essential for learning, in particular for the abstraction and schematisation of knowledge
- Two or more contiguous episodic memory entries provide the structure and process to abstract knowledge from instances for that abstraction
- Is also necessary for "**mental simulation**" of future events
- Mentally reconstructing past episodes and mentally constructing future episodes are two sides of a coin of **mental time travel**
- Generalised episodes serve as an organising point for storing similar episodes

Skill acquisition for cognitive readiness

Skill acquisition means to fill the episodic memory with instances!

- Work experience and practice for becoming an expert means the acquisition of instances
- Instances are saved in episodic memory.
- Learning occurs through the accumulation of instances over repeated task exposure and execution
- The **instances enable a situation to be assessed** in a recognition-primed manner
- The **instances additionally enable mental time travel into the future** in order to estimate the effects of decision
- The assessment and prediction of precision are improved through the acquisition of further episodes

Training design für cognitive readiness
„Staged Process Control Readiness Training“
Stage 1: Task work
Stage 2: Team work & deliberate practice
Training components

- A full scope simulator
- (The sequencing of ) Instances
- Experiential learning
- Component practice
- Briefing
- Debriefing

„Although simulations are used for training, they seemed to be used without much consideration of what has been learned about cognition, training design and effectiveness“ (Salas et al., 2006)
Learning & training with 2-D simulators for cognitive readiness

Conventional DCS synoptic of a distillation column

Control room operator
Learning & training with 3-D simulators for cognitive readiness

3D representation of a distillation column (vertical cylinder on the right), and of auxiliary process units such as reboiler, condenser, and reflux drum (i.e. the three horizontal cylinders from left-bottom corner to the center of the figure)

Field operator


Learning & training with 3-D simulators for cognitive readiness

The pressure gauge in a crude oil refinery appears different at midday (a) and at sunset (b).


But isn’t it too demanding for novices?
Training techniques for beginners

The Gradual Increase in Difficulty
What? **Start with a simple version** of the task and gradually increase its difficulty as learning progresses
Why? In parallel to the increasing task difficulty, skill develops over time, leading to resource demands (intrinsic load) that remain relatively stable over time, leaving enough resources for germane load
Challenge Find out which aspects of a task increase difficulty

Error Prevention: Training Wheels
What? Approach **locks out certain actions** that can have serious unintended consequences
Why? Lower the resource demands of performing, preventing thrashing, and guide resources toward the mastery of mental models or skills to be acquired
Challenge Designing a schedule for release

Part-task training: Fractionating
What? Parts of a task are **performed concurrently** as time-shared tasks, between which attention must be divided
Why? The development of time-sharing skills is an emergent property of the tasks
Challenge Making available more part-task practice time for the part-tasks. For this, automaticity should be developed, due to its consistent mappings, and less time should be given to those parts with little consistency
„Staged Process Control Readiness Training“

Training components
- A full scope simulator
- (The sequencing of) Instances
- Experiential learning
- Component practice
- Briefing
- Debriefing

- Increasing difficulty for novices
- Instances for experts
- Instances for skill retention

Selecting the relevant episodes/instance
E.g. The DIF-Analysis – Difficulty, Importance & Frequency Analysis

“Staged Process Control Readiness Training”

Training components
- A full scope simulator
- (The sequencing of ) Instances
- Experiential learning
- Component practice
- Briefing
- Debriefing

Concrete experience of consequences of actions
Observation & reflection by “zooming in” into central parts of the unit
The formation of abstract concepts and mental models
Testing in (new) situations e.g. real time operation of plant
„Staged Process Control Readiness Training“

Training components
- A full scope simulator
- (The sequencing of ) Instances
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- Debriefing

“component practice” of task components that require time-sharing and attention allocation skills
„Staged Process Control Readiness Training“

Training components
- A full scope simulator
- (The sequencing of) Instances
- Experiential learning
- Component practice
- Briefing
- Debriefing

Briefing: verbal introduction to the instance-based learning episode that “sets the scene”.

Debriefing: verbally guided analysis by the trainer of operator experience to extract rules and explicit knowledge, build up or correct mental models.
Training components **Stage 1:** Task Work Skills

"Staged Process Control Readiness Training"

Training components **Stage 1:**

- Select instances, e.g. based on an event-based analysis
- Convert instances into training scenarios with a high physical and psychological fidelity,
- Sequence instances with increased difficulty, e.g. routine situation, non-routine/normal (planned & unexpected), non-routine/abnormal
- Brief to set the scene, e.g. in the form of a shift handover.
- Debrief with respect to results concerning quality and quantity of goal achievement, disclosure of complex technical processes, summarise cues, actions to be taken and similarities between instances
- Provide component practice for tasks that need to be automatized after introducing the whole task
- Use expanded retrieval practice with retention intervals between instance accumulations

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## Task work simulator training with high psychological & cognitive fidelity

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<td>Cognitive fidelity</td>
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<td>Degree of correspondence between the behavior in a learning setting and the target setting (Stoffregen, Bardy, Smart &amp; Pagulayan, 2003)</td>
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Training components **Stage 2:**

- A full scope simulator
- (The sequencing of ) Instances
- Experiential learning
- Component practice
- Briefing
- Debriefing

**Team Work Skills**

Deliberate practice by means of:

- Decision skill training
- Critical thinking training
- Stress exposure training
- Team training (Team guided self-correction, tram adaptation & coordination training)

Team work training for cognitive readiness

Team Work Skills

Communication
- Information exchange
- Phraseology
- Closed-loop communication

Coordination
- Knowledge requirements

Cooperation
- Mutual performance monitoring
- Back up behavior
- Adaptability
- Team orientation
- Collective efficacy
- Mutual Trust
- Team cohesion

The logic of team work training

Training designed to develop **task-relevant skills** should be directed at individual team members
(Dyer, 1984)

Alternatively, **training teamwork skills**, or those focused on the behaviors and attitudes necessary for effective team functioning, are believed to be best delivered to intact **teams** rather than to individual members
(Cannon-Bowers, Tannenbaum, Salas & Volpe, 1995; Moreland, Argote, & Krishman, 1998)

The logic underlying this position is that **training intact teams provides opportunities for members to integrate their teamwork skills and to jointly practice complex coordinated actions**
(Kozlowski, 1998; Kozlowski, Brown, Weisbein, Cannon-Bowers, & Salas, 2000)
The challenge

Team work skills for non routine/abnormal situations

## Team work simulator training with high action fidelity

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„Staged Process Control Readiness Training“

Training components **Stage 2:**

- Team Work Skills
  - Critical decision training
  - Stress Exposure Training
  - Team Guided Self Correction
  - Team Adaptation & Coordination
  - Expanded retrieval practice

Accumulation of instances during training

On-the-job use, skill retention / refresher training

Training components **Stage 2:**

- Select instances which require collaborative problem-solving that stretch the shooting range of the mind
- Provide decision skill training in order to allow decision strategies of experts to be experienced rather than teaching these skills
- Provide Critical Thinking Training to train constructive controversy within collaborative problem-solving
- Provide Stress Exposure Training to enable operators to cope and maintain performance under stress
- Provide guided team self-correction to support teams in reflecting on their teamwork skills
- Provide team adaptation and coordination training to train the control room team in recognising and changing situational stress levels, in adapting coordination strategies, and the most appropriate conditions under which to use these strategies

Maintaining cognitive readiness through refresher interventions
Cognitive readiness – training for non-routine control-room situations

- Threat: Training methods/duration/frequency (do not) match learning objectives

- Threat: (no) Positive transfer

- Threat: Conditions of performance not considered
  - Routine
  - Non routine/normal
  - Non routine/abnormal

- Threat: (stress/time pressure)

- Learning objectives do not consider performance conditions:
  - Information overload and intransparency
  - Task overload
  - Peer/Supervisor pressure
  - Coping with physiological reaction

- Threat: Skill decay due to long periods of non-use

- Threat: Conditions of performance not considered
  -> HF/Human Error
Cognitive readiness for non-routine situations

Non routine/normal situation: “Start up procedure”

Does work experience in normal operations supports skill retention for non-routine situations?

Results from one of our studies

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Results
„Work experience/ normal operations“

Production

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<th>Time</th>
<th>Initial Training</th>
<th>Retention Assessment</th>
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<tr>
<td>0</td>
<td>1200</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1000</td>
<td>0.5</td>
</tr>
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<td>2</td>
<td>800</td>
<td>1</td>
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<tr>
<td>3</td>
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Secondary Task (mental workload)

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Control Group

Work Experience
That is the reason for Refresher Training

- **Skill retention – research has tradition in military contexts**
  (e.g. Arthur et al, 2010, Bodilly et al., 1986; Farr, 1986, Naylor & Briggs, 1961)

- **Highly automated process industries also face the challenge of skill retention & decay**
  (Bainbridge, 1983; Parasuraman et al. 2000)

“Refresher training aims to re-establish a specific skill level that was acquired at the end of an initial training, which should be re-established after a certain time interval during which the skill was not required to be recalled” (Kluge, Burkolter & Frank, 2012)

The Process Control Task WaTrSim

11 step start-up fixed sequence

Comparing our studies

Refresher interventions
(n = 22 per group)

Results

Production Task

Secondary Task (mental workload, 0-3)

(Explanation: Practice 1 = Practice Study 1)
A different approach to skill retention- supported by gaze guiding (B. Frank & A. Kluge)

Cued recall with gaze guiding – reduction of human errors with a gaze-guiding tool

Step 9: Enable heating HB1
- switch from manual to automatic
- confirm with „OK“

Step 10: Wait until heating HB1 > 60°C

# Design consideration for the gaze guiding tool

<table>
<thead>
<tr>
<th>Name</th>
<th>Example Picture</th>
<th>Parameters</th>
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</table>
| (1) Transparent Overlay   | see Figure 4    | 1) size and position  
2) alpha value for transparency  
3) color  
4) optionally with help text  
5) position of cutout(s) |
| (2) Fixed Arrow           | ![Fixed Arrow](image) | 1) position of arrowhead  
2) arrow direction  
3) color  
4) auxiliary variables for shape of arrow  
5) optional blink interval, initial state and second color |
| (3) Animated Arrow        | ![Animated Arrow](image) | 1) position of arrowhead  
2) arrow direction  
3) color  
4) auxiliary variable  
5) number of steps  
6) step size |
| (4) Frame                 | ![Frame](image) | 1) size and position  
2) shape  
3) color  
4) border thickness  
5) optional blink interval, initial state and second color |
| (5) Attention Marker      | ![Attention Marker](image) | 1) size and position  
2) shape  
3) color  
4) optional blink interval, initial state and second color |
| (6) Help Text             | ![Help Text](image) | 1) size (or adapted to text length) and position  
2) background color of text box and/or of pictogram box  
3) color of the frames  
4) font, font color, font size, font style, line spacing  
5) optionally with one or more pictograms |

Results: Cued recall with gaze guiding – reduction of human errors with a gaze-guiding tool

Take home message

- Inert knowledge is the opposite of cognitive readiness (CR)
- CR= possessing the **task work** and **teamwork knowledge** and skills an operator needs to establish and sustain competent performance in order to be in control in routine, non-routine/normal and non-routine/abnormal situations
- Training is not the barrier- it’s the training outcome!
- CR serves as a active and a passive barrier
- CR is relevant for skills which have not been used for a longer period of time
- CR is relevant for situations which are a) ambiguous and includes b) unanticipated major c) threats to system survival coupled with d) limited time to respond
- Training for CR requires the accumulation of instances by simulator training with high cognitive fidelity
- Team work skills require the practice of team coordination in intact teams with high cognitive and action fidelity
- Normal operations only do not support CR
- Refresher interventions support the retention of cognitive readiness
- Gaze guiding might compensate for CR to some extent (after periods of non-use)
Thanks to my marvelous team for their research effort and for your attention!

Dr. Vera Hagemann → Cognitive foundations of team work
Barbara Frank, M.Sc. → Refresher interventions
Sebastian Brandhorst, M.Sc. → Safety related rule violations
Nikolaj Borisov, Dipl. Inf. → Human Machine Interface of the future

...und Merle Lau, Mike Silbert, Felix Miessen, Alina Tausch, Florian Engel, Julia Sagner, Rebecca Lürmann, Florian Engel (2) as student workers