Metacognition and Self-Regulated Learning: Issues, Interdisciplinary Methods, and Advanced Learning Technologies

Roger Azevedo, Ph.D.
North Carolina State University
Department of Psychology
Laboratory for the Study of Metacognition and Advanced Learning Technologies
Overview

- Metacognition in different subject areas
- Using interdisciplinary methods for measuring metacognition
- Advanced learning technologies to detect, track, model, and foster metacognition
The Future of Learning with Technology?
Global Issues in Metacognition

- Definitions and components of metacognition
- Models of metacognition
- Complex relation between metacognition and cognition (and motivation and affect) and context
- Conscious vs. automatic metacognitive processes
- General vs. domain specificity of metacognition
- Developmental processes in metacognition
- Measurement and assessment of metacognition
- Conditions for the acquisition and instruction of metacognition, and transfer of metacognitive knowledge and skills
- Relation between metacognition and individual differences
- Computers as Metacognitive Tools
**Digital Transformation of Education**

**Interdisciplinary Approach**

<table>
<thead>
<tr>
<th>Psychology</th>
<th>Science of learning with technology</th>
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</thead>
<tbody>
<tr>
<td>(Cog., Dev., Social, Human Factors, Quantitative, IO, Neuroscience, School)</td>
<td>Multiple theoretical approaches</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Education</th>
<th>Focus on product and processes of learning</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Ed. Psych., C&amp;I, STEM, Ed. Tech., Teacher Training)</td>
<td>Focus on cognitive, affective, metacognitive, and motivational (CAMM) processes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cognitive, Learning, and Instructional Sciences</th>
<th>Interdisciplinary, multi-method approaches</th>
</tr>
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<table>
<thead>
<tr>
<th>Computer Science and Engineering</th>
<th>Measuring real-time deployment of CAMM processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>(AI, Affective Computing, HCI, ML, EDM, NLP, computational linguistics, robotics, biomedical)</td>
<td>Self- and externally-regulated learning</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Visual and Media Arts</th>
<th>Human tutoring &amp; adaptivity</th>
</tr>
</thead>
</table>

| | Individual and social aspects of learning |
| | Scaffolding metaphor |
| | Knowledge representations |
| | Role of multiple representations |
| | Acquisition, retention, deployment, and transfer of skills |

| | Design of intelligent technology learning environments |
SMART Lab -- ALTs

- RadTutor
- SICUN Tutor
- SlideTutor
- RiverWeb
- ATS System
- SimSelf
Conceptual and Theoretical Issues
Interdisciplinary Issues (1)

• Integrate models of SRL
  • Cognitive, affective, metacognitive, and motivation (CAMM) processes
  • Phases of SRL with phases of competency in the acquisition of SRL skills

• SRL as an event
  • Agency, cycles, adaptivity, internal and contextual conditions, internal standards, feedback cycles, monitoring and control, adaptation, task perceptions, etc.

• What to support?
  • Cognitive, skills, metacognitive knowledge, monitoring, and control, content knowledge (biology/ecology/medicine/math/breast cancer), domain-specific skills, motivation, and emotions

• When to support?
  • Timing, phases of SRL, phases of learning/performance, content understanding, adaptive & maladaptive behavior (dysregulation)

• How to support?
  • Intelligent pedagogical agents, natural language processing (NLP), interactive interface elements based on real-time diagnosis, open learner models (OLMs)
Interdisciplinary Issues (2)

- **Multi-Agent Systems (research and learning/training tools)**
  - theoretical foundations and assumptions (top-down approach)
  - design principles (interface elements, sensors, etc.)
  - intelligent in adapting to human’s needs in real-time

- **Detect (multi-channel data streams)**
  - methods, sampling, theoretically-driven
  - data types (process, product, and self-report data)

- **Collect Relevant Data**
  - sample (how much, when), temporal alignment, levels of explanation and granularity

- **Analyze and Classify**
  - how, when, why? Within- and across data channels? Why?
  - qualitative and quantitative changes {use EDM and ML techniques}

- **Inferences ➔ Design issues**
  - Modeling, scaffolding, feedback, modifying agent behaviors, ETC.
Self-Regulated Learning (SRL)
(Azevedo, Bannert, Boekaerts, Dunlosky, Efklides, Greene, Hacker, Hadwin, Jarvela, Perry, Metcalfe, Moos, Pekrun, Pintrich, Schraw, Schunk, Veenman, Winne, and Zimmerman)

- Context
- Agency
- Goal(s) and standards(s)
- Internal standards
- Monitoring and control
- Event
- Feedback loops
- Temporal dynamics
- Cyclical processes
- Adaptivity
- Self- vs. other-RL

- Methods to detect, track, & model SRL
- Macro-level and Micro-Level Processes
  - Cognitive, affective, metacognitive, and motivational
- Valence
  - PKA or Sub-goal (relevant vs. irrelevant)
  - JOL- vs. JOL+ (accurate vs. inaccurate)
  - INF+ vs. INF – (correct vs. incorrect)
- Data-driven inferences across and within learners, sessions, data channels
- Data-driven approach to fostering SRL in real-time
Multi-Agent Environments and SRL
SRL with MetaCognitive Tools (Azevedo et al., in press)

Learning Context
- Learning goal(s)
- Instructional resources
- Learning systems (e.g., CBLE)
- External (co-)regulatory agents (e.g., embedded artificial or human agents)
- Feedback system(s) (including levels, types, timing, delivery system)

Task Conditions
- Instructional resources
- Time allotted for task completion (duration of learning session)

Cognitive, Affective, Metacognitive and Motivational (CAMM) Processes
- Prior knowledge of content
- Knowledge of strategies
- Knowledge of the task
- Metacognitive Knowledge and Skills
- Motivational factors and orientations
- Affective states

Learning System (CBLE)
- Non-linear structure
- Multiple representations of information
- Content space
- Levels of learner control
- Levels of scaffolding
- Levels of adaptivity
IPT Model of SRL


**Strengths**
- SRL as an event
- Theory-driven
- Information processing
- Cognitive and metacognitive processes
- Feedback loops
- Dynamic, cyclical and recursive processes
- Control and monitoring are the hubs of SRL

**Challenges**
- Macro-level specification of SRL processes
- Some empirical evidence
Using Interdisciplinary Methods for Measuring Metacognition
International Handbook of Metacognition and Learning Technologies (2013)

Metacognition and Learning Journal
MetaTutor: Learning and Research Tool

**Learning Tool**
- Learners self-regulate by deploying SRL processes during learning and these are later analyzed for evidence of processes.
- Examine effectiveness of agents’ external-regulated learning

**Research Tool**
- Collect fine-grained, time-stamped trace data
- Test-bed for computational algorithms, feedback mechanisms, scaffolding approaches, etc.
- **Induce** specific SRL processes during learning and test adaptivity in real-time
MetaTutor

MetaTutor Modules

- **Timer:** Shows time remaining in the learning session.
- **Overall Learning Goal:** Set by either the experimenter or teacher.
- **Agents:** There are four pedagogical agents assigned to different SRL processes.
- **Communication:** Narrative of agents' verbalization.
- **Dialogue History:** Learner-Agent Dialog History.
- **Subgoals:** The learner can generate several subgoals for the session.
- **Table of Contents:** Topics and subtopics of the content.
- **Learning's Metacognitive Judgments Area:**
- **Test Content Area:** Science Content.
- **Image Content Area:** Stylized representations of content.
- **SRL Palette:** Learners may employ any of these SRL processes during learning.
- **Discrimination Task:** Learner identifies proper use of SRL processes during training.
- **Testing Mode:** Learner demonstrates use of SRL processes.
- **SRL Processes:**
- **Identification Task:** Learner watches video clip and indicates which SRL process is being used by human on video clips.
MetaTutor Layouts

- Normal View
- Full View
- Notes View
- User Input With Content
- User Input Without Content
- Quiz View
SRL with MetaTutor

Overall Task

Overall Learning Goal

Sub-Goal 1
Sub-Goal 2
Sub-Goal 3
Sub-Goal 4

KNOWLEDGE CONSTRUCTION ACTIVITIES

Reading Pages
Inspecting diagrams

COGNITIVE PROCESSES

Take Notes
Drawing
PKA
Summarize
Knowledge Elaboration
Inferences
Self-test
Re-read
COIS

METACOG. PROCESSES

JOL
FOK
Monitoring Use of Strategies
Content Evaluation
Monitoring Progress Towards Goals
Time Monitoring

AFFECTIVE PROCESSES

Anger
Fear
Sadness
Joy
Disgust
Surprise
Neutral
Confusion
Frustration
Contempt

ASSESSMENTS

Pretest
Quizzes
Summaries
Metacognitive Judgments
Posttest
Detecting, Tracing, and Modeling SRL Processes, Skills, and Domain Knowledge

(Azevedo, Moos, Johnson, & Chauncey, 2010)

- Declarative knowledge gains
- Setting Goals
- Mental Model Shift
- Development of Self-Efficacy

Time ($t_0$ to $t_n$)

Trace Data

Product Data

Self-Report Data
## Product, Process, and Self-Report Data

<table>
<thead>
<tr>
<th>Data Type(s)</th>
<th>Specific Method/Tool</th>
<th>Cognitive</th>
<th>Metacognitive</th>
<th>Motivation</th>
<th>Affective</th>
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<tbody>
<tr>
<td>Process Data</td>
<td>Screen Recordings</td>
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<td></td>
<td>Concurrent Think-Alouds</td>
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<td>Eye-tracking</td>
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<td>Log-Files</td>
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<td></td>
<td>Facial Expressions</td>
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<td></td>
<td>Physiological Data (sensors)</td>
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<tr>
<td>Product Data</td>
<td>Quizzes</td>
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<td></td>
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<tr>
<td></td>
<td>Summaries</td>
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<tr>
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<td>Pretest-Posttest-Transfer Tests</td>
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<td>Self-Report</td>
<td><strong>Self-Report Measures</strong></td>
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</tr>
<tr>
<td></td>
<td>(AEQ, Agent Perception, OMQ)</td>
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<tr>
<td></td>
<td>Metacognitive Judgments</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Other</td>
<td>Interface (elements)</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Learner-Agent(s) Dialogue</td>
<td></td>
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</tr>
</tbody>
</table>
Collecting Data with MetaTutor
SRL with MetaTutor

Sub-Goal #1

90 sec.

CE+  Reading  JOL+  COIS  SUM+  JOL-

Sub-Goal #2

60 sec.

10 sec.

CE+  Reading  JOL+  COIS  SUM+  JOL-
“Externalizing” Metacognitive Processes—Interface Elements
Sample Multi-Channel Data
## Quantitative Results (Azevedo et al., 2012)

<table>
<thead>
<tr>
<th></th>
<th>No Prompt Condition</th>
<th>Prompt Only Condition</th>
<th>Prompt and Feedback Condition</th>
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<tbody>
<tr>
<td><strong>Overall Learning Time (min.)</strong>*</td>
<td>Mean (SD)</td>
<td>Mean (SD)</td>
<td>Mean (SD)</td>
</tr>
<tr>
<td></td>
<td>97.94 (12.42)</td>
<td>68.31 (11.18)</td>
<td>56.84 (11.82)</td>
</tr>
<tr>
<td><strong>Number of Pages Visited+</strong></td>
<td>38.87 (03.84)</td>
<td>33.26 (08.39)</td>
<td>23.56 (10.07)</td>
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<tr>
<td><strong>Overall Time on Page (min.)</strong>*</td>
<td>1.07 (06.66)</td>
<td>0.99 (00.50)</td>
<td>1.32 (01.06)</td>
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<tr>
<td><strong>Overall mean time on Diagrams (min.)</strong>*</td>
<td>0.54 (0.46)</td>
<td>0.75 (0.51)</td>
<td>1.05 (00.99)</td>
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<tr>
<td><strong>Number of Sub-Goals set During Learning</strong></td>
<td>4.70 (01.72)</td>
<td>4.13 (01.29)</td>
<td>3.04 (00.98)</td>
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<tr>
<td><strong>Mean Time Spent on Each Self-Set Sub-Goals (min.)</strong>*</td>
<td>23.30 (12.18)</td>
<td>27.77 (09.96)</td>
<td>41.39 (18.60)</td>
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<tr>
<td><strong>Learning Efficiency (%)</strong></td>
<td>23.10 (06.00)</td>
<td>28.90 (10.40)</td>
<td>34.30 (13.60)</td>
</tr>
</tbody>
</table>

+ out of 41 pages
* $p < .05$
SRL Processes used during Learning with MetaTutor

(3) Planning
Prior Knowledge Activation, Creating Sub-Goals (+/-)
Recycling Goals in Working Memory

(7) Metacognitive Monitoring
Judgment of Learning (+/-), Feeling of Knowing (+/-)
Monitoring Use of Strategies (+/-), Monitoring Progress Towards Goals (+/-), Time Monitoring (+/-), Content Evaluation (+/-), Expecting the Adequacy of Information (+/-)

(11) Learning Strategies
Coordinating Informational Sources, Drawing, Inferencing (+/-), Knowledge Elaboration, Summarization (+/-), Re-Reading, Self-Test, Review Notes, Take Notes, Free Search, Rehearsal

(2) Handling Task Difficulties and Demands
Help-Seeking Behavior, Task Difficulty
## Frequency of Use and Duration of SRL Processes

<table>
<thead>
<tr>
<th>SRL Process</th>
<th>Raw Frequencies</th>
<th>Mean (SD)</th>
<th>Mean Duration of SRL Process (sec.)</th>
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<tr>
<td><strong>Monitoring</strong></td>
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<td>Content Evaluation (+)</td>
<td>[57]</td>
<td>1.30 (2.42)</td>
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<tr>
<td>Content Evaluation (-)</td>
<td>[73]</td>
<td>1.66 (2.52)</td>
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<tr>
<td>Expectation of Adequacy of Content (+)</td>
<td>[15]</td>
<td>.34 (.75)</td>
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<tr>
<td>Expectation of Adequacy of Content (-)</td>
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<td>.09 (.36)</td>
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<td>Feeling of Knowing (+)</td>
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<tr>
<td>Feeling of Knowing (-)</td>
<td>[81]</td>
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<tr>
<td>Judgment of Learning (+)</td>
<td>[161]</td>
<td>3.66 (6.18)</td>
<td>0:00:03</td>
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<td>Judgment of Learning (-)</td>
<td>[56]</td>
<td>1.27 (2.49)</td>
<td>0:00:03</td>
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<tr>
<td>Monitor Progress Toward Goals</td>
<td>[13]</td>
<td>.30 (.79)</td>
<td>0:00:09</td>
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<tr>
<td>Monitor Use of Strategies</td>
<td>[11]</td>
<td>.25 (.89)</td>
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<tr>
<td>Time Monitoring</td>
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<td>.63 (1.45)</td>
<td>0:00:03</td>
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<td><strong>Learning Strategies</strong></td>
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<tr>
<td>Coordination of Informational Resources</td>
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<tr>
<td>Draw</td>
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<tr>
<td>Inference (+)</td>
<td>[72]</td>
<td>1.64 (4.27)</td>
<td>0:00:30</td>
</tr>
<tr>
<td>Inference (-)</td>
<td>[52]</td>
<td>1.18 (1.86)</td>
<td>0:00:07</td>
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<tr>
<td>Knowledge Elaboration</td>
<td>[15]</td>
<td>.34 (.91)</td>
<td>0:00:07</td>
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<td>Memorization</td>
<td>[98]</td>
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<td>Mnemonic</td>
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<td>0:00:04</td>
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<tr>
<td>Read Notes</td>
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<td>Re-Read</td>
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<tr>
<td>Summarize (+)</td>
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<td>[653]</td>
<td>14.86 (13.56)</td>
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<tr>
<td>Summarize (-)</td>
<td></td>
<td>[517]</td>
<td>11.75 (11.15)</td>
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<tr>
<td>Self Question</td>
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<td>[23]</td>
<td>.52 (.95)</td>
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<td>Self-Test</td>
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<td>[70]</td>
<td>1.59 (3.14)</td>
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<tr>
<td>Take Notes</td>
<td></td>
<td>[1018]</td>
<td>23.14 (23.88)</td>
</tr>
</tbody>
</table>
Reconstructed Trace Data
Note-Taking and Drawing
(Trevors, Duffy, & Azevedo, 2011, 2012, 2013a,b)
Log-Files Collected during Learning with MetaTutor

- Extract > 300 variables
- Time stamps for various behaviors
  - Switching between topics and multiple representations of information
  - Classification of navigational paths
  - Time spent on content, sub-topics, pages, images, animations, etc.
  - Time spent on pretest, posttest, embedded quizzes, “listening” to agent, delay between agent scaffolding and subsequent learner action, etc.
  - Accuracy of embedded testing (e.g., pretest, quizzes, summaries, etc.)
  - Acquisition of and efficacy in the use of SRL skills during extended learning sessions
- Coordinate log file trace data, think-aloud protocols, video coding, and eye-movements
Eye-Tracking: Multiple Representations & Affect Detection

- Selection, organization, and integration of multiple representations (Feyzi-Behnagh et al., 2012, 2013)

- Examine evidence of cognitive and metacognitive processes involved in the integration of multiple representations of information (Azevedo et al., 2013)

- Illustration of gaze trends for engaged (curious, not bored) and disengaged (bored, not curious) students

- Predict engagement and disengagement based on gaze behavior patterns in real-time (Jaques et al., under review)
Physiological Data and Facial Expressions
Integration of Data Channels
(screen recording, think-aloud, and eye-tracking)

Good Self-Regulating Learner
Temporal Alignment and Integration of Data Channels
(pupil dilation, TAs, learner-agents dialogue moves, emotions, agents’ instructional scaffolding and feedback)

Agent Scaffold
Learner Talks
Learner (silent) and typing
Agent Feedback

Emotional States
Integration of Data Channels
(facial expressions, physiological responses, screen recording, agent scaffolding and feedback + emotions annotator tool)
Learning Trajectories: Knowledge Gains and SRL Processes
## Data-Driven Inferences

<table>
<thead>
<tr>
<th>Behavioral Signatures</th>
<th>Indicative of an SRL Process?</th>
<th>Make a Decision?</th>
<th>Instructional Implications</th>
</tr>
</thead>
</table>
| **Log-Files**                                                                        | *Learners’ and agents’ behaviors  
*Sequence and selection, and time on text and diagrams  
*Quiz scores (at the page-level and across interface layouts)  
Infer—Learning Strategy?  
*Skimming, COIS, knowledge elaboration, etc.?  
Infer—Metacognitive Monitoring Processes?  
*Monitoring Progress Towards goals, etc.?  
Infer—General Aspects of SRL?  
*Adaptivity (from page-level and session-level) | Time thresholds, temporal sequencing, coding scheme, machine learning, quality, and quantity, etc. | Model, Scaffold, and Fade  
*what, when how, why, and by whom?                                                                                                                                                                                                                                                  |
| **Eye-Tracking**                                                                     | *Learners’ gaze behavior, fixations, regressions, saccades, etc. (at the page-level and across interface layouts)  
Infer—Learning Strategy?  
*Skimming, COIS, knowledge elaboration, etc.?  
Infer—Metacognitive Monitoring Processes?  
*Content evaluation, JOL, etc.  
Infer—Affective States?  
*Confusion, boredom  
Infer—General Aspects of SRL?  
*Adaptivity (at the page-level only?) | Time thresholds, temporal sequencing, machine learning, quality, and quantity, etc. | Model, Scaffold, and Fade  
*what, when how, why, and by whom?                                                                                                                                      |
Current SMART Lab Projects...

- **Conceptual and Theoretical Issues**
  - Extend models and theories of SRL to account for CAMM processes [prior / during / following]
  - SRL, ERL, CoRL, and SSRL {human, artificial agents, IVH or combo}

- **Methodological and Analytical Issues**
  - Test existing interdisciplinary methods and analytical techniques (e.g., ML, EDM, sensors)
  - Develop tools to integrate and analyze multi-channel data
  - Intra- vs. inter-individual differences // time series designs
  - Contribute to and extend computational models of CAMM in multi-agent systems

- **Education and Training Issues [across multiple contexts]**
  - ALTs {serious games} in different contexts {lab, classrooms, informal settings, workplace, emergency room, operating room}
  - Developmental differences, novice-expert differences, individual differences
  - Solo learning, collaborative problem solving, team problem solving
  - 21st Century Skills (SRL, problem solving, conceptual understanding)
  - Scaffolding, modeling, fading
  - Transfer of SRL skills
Future Directions

- Develop new representational tools (for learners, teachers, and researchers)
  - What, when, and how to represent data (e.g., raw [EDA] vs. summarized)?

- What to measure and represent?
  - Internal standards, monitoring and control of CAMM processes, task perceptions, etc.
  - Fluctuations in CAMM processes during complex learning—behavioral signatures
  - Changes in SRL processes over time (e.g., chapter, semester, academic year, etc.)
  - Learning outcomes, transfer of skills, conceptual understanding, impact of ERL (e.g., learner compliance), collaborative skills, etc.

- When to measure?
  - Continuously vs. periodically; control of data stream; accessible to others; etc.
  - How much sampling of data is needed before it is analyzed and represented to researchers and learners (and teachers)?

- How to measure and analyze the data (in real-time?)?
  - Classroom discourse, human-agent dialogue, log-files, self-report measures, sensors (physiological and computer algorithms), facial expressions, etc.
  - Educational data mining, machine learning, learner analytics, computational linguistics, etc.
Challenges and Opportunities

• **Challenges**
  – Temporally align and converge multi-channel data
  – Develop descriptive and predictive models of CAMM processes
  – Develop learning trajectories for CAMM knowledge and skills
  – Data-driven inferences based on multi-channel data
  – Statistical and computational methods to analyze data
  – Inform the design of adaptive CAMM scaffolding for ALTs

• **Opportunities**
  – Transform and augment current ALTs for STEM learning
    • new generation of ubiquitous, intelligent systems (e.g., affectively-responsive)
  – Scalability
    • from lab to classroom and non-formal learning contexts
    • complex, professional contexts
  – Enhance training of STEM education and 21st Century skills
  – Broaden interdisciplinary boundaries and collaborations within academia (e.g., neuroscience, robotics, biomedical engineering) and industry (e.g., serious games, nanotechnology, biometrics, textiles—smart clothing)
Current Projects and Collaborations

- Affect and MetaTutor (NCSU, McGill, U Memphis, IIT)
- SimSelf: Embodied agents for SRL and STEM learning (NCSU, Vanderbilt, McGill)
- Self-regulated learning and emotions with Crystal Island (NCSU)
- Affect and Co-Regulated Learning in a Medical Simulation Environment [internal medicine and pediatrics] (NCSU, McGill, MUHC)
- MetaProf: Using MetaTutor in higher education (NCSU, McGill)
- Computational modeling of affect with MetaTutor (NCSU, McGill, UBC)
- Emotion regulation and breast cancer patients (NCSU, McGill, MUHC)
- Epistemic beliefs, emotions, and SRL (NCSU, McGill, U. of Munich, & USC)
- Personal health informatics (NCSU, McGill, U of Sydney)
- Physiological correlates of SRL during learning (NCSU, McGill, Central Queensland U, MediaCity, Åbo Akademi U)
- Multi-agent co-regulated learning and physics (NCSU, McGill, Concordia U., Dawson, and Vanier College)
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  [http://smartlaboratory.ca](http://smartlaboratory.ca)

  razeved@ncsu.edu

Thank you!

Questions?