Cognitive Task Analysis: Think Alouds and Difficulty Factors Assessment

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Overview

- Cognitive Task Analysis
  - What is it? Why do it?
- CTA methods
  - Difficulty Factors Assessment
  - Think Aloud
- Hands-on exercise

Cognitive Task Analysis

- Techniques to specify cognitive structures & processes associated with task performance
  - Structured interviews of experts
  - Think alouds of experts & novices performing tasks
  - Computer simulations of human reasoning

Unpacking & repacking expertise: Chick sexing

- Experts don’t know, what they know
  - 98% accurate after years of on-the-job training
- Interviews led to design of “pictures in which critical features of various types were indicated”
- After just minutes of instruction, novices brought to 84% accuracy!

Cognitive Task Analysis Improves Instruction

Studies: Traditional instruction vs. CTA-based

- Med school catheter insertion (Velmahos et al., 2004)
  - Sig greater pre to post gain
  - Better with patients on all four measures used
  - Example: Sig fewer needle insertion attempts!
- Other examples
  - Radar system troubleshooting (Schaafstal et al., 2000)
  - Spreadsheet use (Merrill, 2002)
- Meta-analysis, 7 studies: 1.7 effect size!
  (Lee, 2004)

Isn’t knowledge analysis done for long-standing academic domains?

- Hasn't all this been worked out?
- Surely by now we understand the content of, say, Algebra?

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Need for a Knowledge Decomposition Methodology

- Good instruction targets the edge of students’ knowledge, what is “just-learnable”
- Need a method for decomposing a topic into knowledge components
  - What components are learners’ missing?
  - What order do they acquire these components?
  - Which components are particularly hard to acquire?
  - What “hidden skills” must be acquired?
- Knowledge decomposition guides design of:
  - problem solving activities, tutor interface, cognitive model, hints and bug messages, problem sequence
Knowledge Decomposition through Difficulty Factors Assessment (DFA)

- Goal: Identify what is "just learnable" for students at different levels of competence
- The DFA methodology:
  1. Identify possible problem difficulty factors
     - Use think aloud or analytic task analysis
  2. Create test items & forms; Administer
  3. Analyze results:
     a. Main effects and interactions
     b. Strategies and errors
  4. Create a cognitive model
  5. Create a “developmental model” or “learning progressions”

Which problem is hardest for beginning algebra students?

Story Problem
As a waiter, Ted gets $6 per hour. One night he made $66 in tips and earned a total of $81.90. How many hours did Ted work?

Word Problem
Starting with some number, if I multiply it by 6 and then add 66, I get 81.90. What number did I start with?

Equation
\[ x \times 6 + 66 = 81.90 \]

Algebra Student Results: Story Problems are Easier!

Part of a larger “Difficulty Factors Assessment”

- Difficulty factors involved
  - Presentation type
    - Story, Word, vs. Equation
  - Unknown position
    - Result-unknown vs. start-unknown
  - Number type
    - Whole vs. decimal numbers
- Multiple quiz forms
- Detailed strategy & error analysis

Algebra equations are like a foreign language -- takes extensive experience to acquire.

More Common: Informal Strategies

Experts Blind Spot
Algebra teachers worst at recognizing algebra student difficulties

What’s behind expert blind spot?

- Self-reflection on current cognition, biased memory of past learning
- Aware of verbally-mediated reasoning
  - False inference: More words => more thinking
- Not aware of implicit processing & learning
  - Fluent algebra language processing requires *extensive implicit learning*
  - Our minds are continually engaged in pattern induction, analogy, chunking, strengthening ...

Using Cognitive Task Analysis to design better algebra instruction

- Inductive support strategy
  - Help students generalize abstract math from their own intuitive concrete solutions
  - Similar to “progressive formalization” or “concreteness-fading” (Golstone & Son, 05)
- Test idea with an *in vivo experiment*

Parametric Study: Textbook vs. Cognitively-Based Design

<table>
<thead>
<tr>
<th>Textbook (Symbolize first)</th>
<th>Inductive Support (Solve &amp; then symbolize)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. 35 + 42h = d</td>
<td>1. 35 + 42h = d</td>
</tr>
<tr>
<td>2. 35 + 42*3 = 161</td>
<td>2. 35 + 42*3 = 161</td>
</tr>
<tr>
<td>3. 35 + 42*4.5 = 224</td>
<td>3. 35 + 42*4.5 = 224</td>
</tr>
<tr>
<td>4. 35 + 42h = 140</td>
<td>4. 35 + 42h = 140</td>
</tr>
</tbody>
</table>

Plumbing Co. charges $42 per hour plus $35 for the service call
1. ... write an expression ...
2. How much for a 3 hour call?
3. What will bill be for 4.5 hours?
4. Find hours when bill is $140

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What is a Think-Aloud Study?
Basically, ask a users to “think aloud” as they work...
...on a task you want to study
...while you observe & audio or videotape
...either in context (school) or in lab
...possibly using paper/storyboard/interface you are interested in improving

The Roots of Think-Aloud Protocols

• Allen Newell and Herb Simon created the technique in 1970s
• Anders Ericsson & Herb Simon’s book
  – Explained & validated technique

The Cognitive Psychology Theory behind Think-Aloud Protocols

• People can easily verbalize the linguistic contents of Working Memory (WM)
• People cannot directly verbalize:
  – The processes performed on the contents of WM
    • Procedural knowledge, which drives what we do, is outside our conscious awareness, it is “tacit”, “implicit” knowledge.
    • People articulate better external states & some internal goals, not good at articulating operations & reasons for choice
  – Non-linguistic contents of WM, like visual images
• People can attempt to verbalize procedural or non-linguistic knowledge, however, doing so:
  – May alter the thinking process (for better or worse)
  – May interfere with the task at hand, slowing performance
How to Collect Data in a Think-Aloud Study
(Gomoll, 1990, is a good guide)

1. Set up observation
   - write tasks
   - recruit students
2. Describe general purpose of observation
3. Tell student that it’s OK to quit at any time
4. Explain how to “think aloud”
   - give a demonstration
   - give an unrelated practice task, e.g., add digits
5. Explain that you will not provide help
6. Describe tasks
7. Ask for questions before you start; then begin observation
   - say “please keep talking” if the participant falls silent for 5 seconds or more
   - be sensitive to a severe desire to quit
8. Conclude the observation

Example: Think Alouds in Statistics Tutor Development

- Task: Exploratory Data Analysis
  - Given problem description and data set
  - Inspect data to generate summaries & conclusions
  - Evaluate the level of support for conclusions
- Example Problem
  In men’s golf, professional players compete in either the regular tour (if they’re under 51 years old) or in the senior tour (if they are 51 or older). Your friend wants to know if there is a difference in the amount of prize money won by the players in the 2 tours. This friend has recorded the prize money of the top 30 players in each tour. The variable money contains the money won by each of the players last year. The variable tour indicates which tour the player competed in, 1=regular, 2=senior. The variable rank indicates player rank, 1=top in the tour.

Thanks to Marsha Lovett!

Rational Task Analysis of Major Goals

- Inspired by ACT-R theory
- Break down task:
  - 7 major goals
  - Each goal has involves multiple steps or subgoals to perform
  - Key productions react to major goals & set subgoals

Sample Transcript

<table>
<thead>
<tr>
<th>L#</th>
<th>Participants words &amp; actions</th>
<th>Annotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Oh, okay.</td>
<td>Goal 1</td>
</tr>
<tr>
<td>2</td>
<td>So we need to, he wants to know whether there is a</td>
<td>Goal 2</td>
</tr>
<tr>
<td>3</td>
<td>difference in the amount of prize money, the amount of</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>money won by players in the two tours.</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>So, I think this is the prize money, uh, money contains the</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>prize money won by each of these players.</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Tour indicates which tour the player competes in.</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Well, you don’t really need rank, in order to solve this, right?</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Cause like, well, I don’t know.</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Um... I’m gonna do a boxplot... ...</td>
<td>Goal 4</td>
</tr>
<tr>
<td>11</td>
<td>[Subject uses statistics package to make a boxplot]</td>
<td>Goal 5</td>
</tr>
<tr>
<td>12</td>
<td>oh, cool (laugh) I did it.</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>All right, uh, so just looking at the average.</td>
<td>Goal 6</td>
</tr>
<tr>
<td>14</td>
<td>It looks like the people in the senior tour get less money.</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Um, and there’s a lot less variation in the amount of money</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>that, like all the prizes.</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>A couple little outliers in each which means like, I don’t</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>know, like some people won, like a lot of money at a time...</td>
<td></td>
</tr>
</tbody>
</table>
Key observations about this verbal report

- No evidence for goal 3 “characterize the problem”
  - Line 10: student simply jumps to selecting a data representation (goal 4) without thinking about why.
- No evidence for goal 7 “evaluate evidence”

Inspiration for Production Rules (Knowledge Components)

- Missing production (to set goal 3): Characterize problem
  If goal is to do an exploratory data analysis & relevant variables have been identified then set a subgoal to identify variable types
- Buggy production (skipping from goal 2 to 4): Select any data representation
  If goal is to do an exploratory data analysis & relevant variables have been identified then set a subgoal to conduct an analysis by picking any data representation

Comparing Think Aloud Results with Rational Task Analysis

- Percentages to the right of each step represent the percentage of students in the think-aloud study who showed explicit evidence of engaging in that step.
- Step 3 is totally absent!
  - A tutor can help students to do & remember to do step 3

Statistics Tutor Design: Explicitly prompts students to engage in critical subgoals
Students are prompted to complete critical subgoal #3 from CTA

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Cognitive Task Analysis Exercise

- Use Think Aloud to design a Difficulty Factors Assessment
- Find someone next to you to work with
  - I will give two problems
  - Take turns giving a think-aloud solving these next two problems

Try this ...

- One person think aloud while solving this problem. You can use paper. Other person is experimenter.
  
  Experimenter: Remember to say “keep talking” whenever participant is silent

- Ready ...
- What is $5 \div \frac{3}{4} =$ ?
Now this ...

• Switch roles:
  – Other person think aloud
  – What’s written on paper is part of TA
  – Did the experimenter say ”keep talking”?

• Ready ...

• If 5 yards of ribbon are cut into pieces that are each 3/4 yard long to make bows, how many bows can be made?

Think about student thinking ...

• Which will be easier?

• Why?

• Strategy & error analysis:
  – What strategies will students use?
  – Will there be differences in strategy selection between problem types?
  – What errors might account for observed differences?

How could you design a DFA to test your hypotheses?

• Can you put these two problems on the same quiz form?
  – Why not? What can you do instead?

• What other factors might be involved?
  – Size of the numbers--big nums discourage informal strategy
  – “Tempting” nums like 6 ÷ 3/5
  – Order: context first vs. context second

“Latin Square” Design

<table>
<thead>
<tr>
<th></th>
<th>Form 1</th>
<th>Form 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Context</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Context</td>
<td>Form 2</td>
<td>Form 1</td>
</tr>
</tbody>
</table>

• Don’t give problems with same answer on same form
• Can give problems with both values of a difficulty factor
• Example above
  – Students using either Form 1 or Form 2 will get both a No-Context & a Context problem
  – But, two forms ”counter balance” the number types
Cognitive Task Analysis Summary

- A cognitive model of student reasoning & learning in a specific domain guides instructional design
- Do Cognitive Task Analysis (CTA) to develop a cognitive model
  - Rational CTA: Articulate knowledge components in English (or in a computer simulation like a production rule system)
  - Empirical CTA methods: Think Aloud, Difficulty Factors Assessment, educational data mining techniques ...
- Think aloud: Rich data on student thinking processes
  - Best way to develop good intuitions about student thinking!
- Difficulty Factors Analysis
  - Quickly & systematically focus in on what’s hard for learners

Think Aloud activity you might try with another team

- Team A members do Think Alouds with Team B members
  - Alternate experimenter & participant roles
  - Experiment presents your task
  - Participant performs task & thinks aloud
- First round:
  - A1 is experimenter, B1 is participant
  - A2 is participant, B2 is experimenter
- Second round -- switch roles
  - A1 is participant, B1 is experimenter
  - A2 is experimenter, B2 is participant

Strategies for identifying potentially interesting difficulty factors

- Ask yourself & teachers: What’s most difficult for students to learn in this class?
- Add or reduce complexity in an existing test item
  - Add complexity: multiple operations, type & scale of numbers involved, distractors, abstract formalisms
  - Reduce complexity by drawing on prior knowledge
    - Place problem in familiar context
    - Use concrete instances instead of abstractions
    - Use a concrete pictorial representation
Extended Example of a Difficulty Factors Assessment design


Symbolization Task

EXAMPLE PROBLEM
Sue made $72 washing cars. She decided to spend “m” dollars on a present for her mom and then use the remainder to buy presents for each of her 4 sisters. Write an expression for how much she can spend on each sister.

Example answer: (72 - m) / 4

Rational Cognitive Task Analysis: How Does One Symbolize?

- Comprehend
  - Figuring out the math operations involved (e.g., “... remainder ...” -> “subtract“)

- Produce symbols
  - “subtraction” -> “-”
  - Order of operations, getting paren’s right
  - Being to able to write “embedded clauses”, expr -> num op num
  - expr -> expr op expr

Select Difficulty Factors to identify challenging cognitive processes

Potentially challenging cognitive process
1. Reading story problem
2. Avoiding shallow processing
3. Writing expressions with variables
4. Composing 2-op symbolic sentences

Associated difficulty factor manipulation
1. Comprehension hints vs. none
2. Distractor numbers vs. none
3. Variable vs. numbers
4. Decomposed (two 1-op) vs. composed (one 2-op)
A) Ann is in a rowboat in a lake. She is 800 yards from the dock. She then rows for "m" minutes back towards the dock. Write an expression for the distance Ann has rowed.

B) Ann is in a rowboat in a lake. She then rows for "m" minutes back towards the dock. Write an expression for Ann's distance from the dock.

P1 Decomposed Problem
A) Ann is in a rowboat in a lake. She is 800 yards from the dock. She then rows for "m" minutes back towards the dock. Write an expression for Ann's distance from the dock.

P2 Distractor Problem
Ann is in a rowboat in a lake that is 2400 yards wide. She is 800 yards from the dock. She then rows for "m" minutes back towards the dock. Ann rows at a speed of 40 yards per minute. Write an expression for Ann's distance from the dock.

P3 Comprehension Hint
[Core Problem]
Hint 1: Ann's distance from the dock is equal to the 800 yards she started out from the dock minus the distance she has rowed in "m" minutes.

Hint 2: The distance she has rowed in "m" minutes is equal to the 40 yards she rows per minute multiplied by the "m" minutes it takes her.

P4 No Variable Problem
Ann is in a rowboat in a lake. She is 800 yards from the dock. She then rows for 11 minutes back towards the dock. Ann rows at a speed of 40 yards per minute. Write an expression for Ann's distance from the dock.

Focus on two of these factors: Comprehension & Decomposition

CORE PROBLEM
Sue made $72 washing cars. She decided to spend "m" dollars on a present for her mom and then use the remainder to buy presents for each of her 4 sisters. She will spend the same amount on each sister. How much can she spend on each sister?

COMPREHENSION HINT VERSION
[Core problem followed by these hints.]
Hint 1: The amount Sue spends on all sisters is equal to the $72 she earned minus the "m" dollars she gives to Mom.

Hint 2: The amount Sue spends on each sister is equal to the amount Sue spends on all sisters divided by 4 (the number of sisters she has).

DECOMPOSED VERSION
Sue made $72 washing cars. She decided to spend "m" dollars on a present for her mom. How much does she have left?

Sue has "x" dollars for presents for each of her 4 sisters. She will spend the same amount on each sister. How much can she spend on each sister?

Composition Effect => Symbol production not text comprehension

Overall Results

<table>
<thead>
<tr>
<th>Difficulty factor</th>
<th>Significant Effect?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comprehension hints</td>
<td>No</td>
</tr>
<tr>
<td>Distractor numbers</td>
<td>Yes</td>
</tr>
<tr>
<td>Variable vs. numbers</td>
<td>No</td>
</tr>
<tr>
<td>Decomposed (two 1-op) vs. composed (one 2-op)</td>
<td>Yes</td>
</tr>
</tbody>
</table>

No comprehension hint effect: Students do not have much trouble comprehending problems, e.g., understanding “for each of” as “divides”.

Composition effect: Students have trouble composing two operator algebraic sentences -- even when they understand both operations!
Error Analysis

**CORE PROBLEM**
Sue made $72 washing cars. She decided to spend "m" dollars on a present for her mom and then use the remainder to buy presents for each of her 4 sisters. She will spend the same amount on each sister. How much can she spend on each sister?

**DECOMPOSED VERSION**
Sue made $72 washing cars. She decided to spend "m" dollars on a present for her mom. How much does she have left?

**Correct Answer:** \( \frac{72 - m}{4} \)

**Basic errors:**
- Wrong operator: \( (72 - m) * 4 \)
- Argument order: \( 4 / (72 - m) \)
- Composition errors:
  - Invented notation: \( 72 - m = n / 4 \)
  - Missing parentheses: \( 72 - m / 4 \)
  - Subexpression: \( 72 - m \) or \( m / 4 \)

**Example Production Rules**

- **Works on decomposed problems:**
  If the goal is to symbolize quantity \( =Q \),
  \( =Q \) is the result of applying operator \( =Op \) to \( =Num1 \) and \( =Num2 \).
  \( =Op \) has symbol \( =Op-Sym \)
  Then write \( "=Num1 =Op-Sym =Num2" \)

- **Works on composed (w/o parens!):**
  If the goal is to symbolize quantity \( =Q \),
  \( =Q \) is the result of applying operator \( =Op \) to expression
  \( =Expr1 \) and \( =Expr2 \)
  \( =Op \) has symbol \( =Op-Sym \)
  Then write \( "=Expr1 =Op-Sym =Expr2" \)

Producing Symbolic Sentences is Particularly Hard

- **Decomposed success** --> Students can *comprehend* of text
- **Variable success** --> Producing is hard even without variable: "(96 - 72)/4" "800 - 40*3"
- **Composed failure -->** Cannot *produce* 2-op sentences:
  - \( (x - 72)/4 \)
  - \( 800 - 40m \)

This Analysis has Subtle Implications for Instruction

- **Inductive support:**
  Have students solve problems using small integers before writing symbols

- **Create problems to isolate key difficulty**
  - “Substitute \( x-74 \) for \( w \) in \( w / 4 \)”
  - Apparently unrelated substitution exercises may improve story problem symbolization!