

Causal Model Search in Educational Research

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1. INTRODUCTION



“Online” Educational Data

Data Pouring in From:

- Computer Tutors
- Online courses
- Virtual Labs



Pittsburgh Science of Learning Center

<http://www.learnlab.org>

- NSF center on learning science (1 of 6)
- Cognitive Tutors (Algebra, Physics, Geometry, etc.)
 - ~600,000 HS students
 - Recent independent evaluation (180 schools): twice as much algebra learned
- Datashop
 - ~500 publicly accessible datasets in standardized format
 - Analytic tools for analyzing these data

The screenshot shows the Cognitive Tutor Algebra 1 interface. It includes a scenario window with a word problem about an aircraft being raised from a depth of 12,700 feet. A graph window shows a plot of Depth (Feet) vs Time (Hours) with a single data point at (5, -6700). A worksheet window shows a table with columns for Time (Hours) and Depth (Feet), and rows for expressions and values. A solver window shows the steps: $-7625 + 185H = -12790$, Add 7625, $185H = -5,165$, Divide by 185, and $H = -1,033/37$. A skills list is also visible.

TIME	DEPTH
HOURS	FEET
Unit	
Expression	$-7625 + 185H$
1	-5
2	5
3	-27,9189...
4	

A 2000-kg car in neutral at the top of a 20.0 deg inclined driveway 20.0 m long slips its parking brake and rolls down. Assume that the driveway is frictionless.

What is the magnitude of the velocity of the car when it hits the garage door?

Answer:

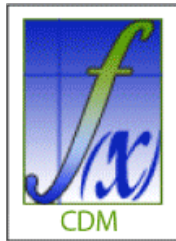
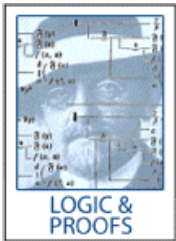
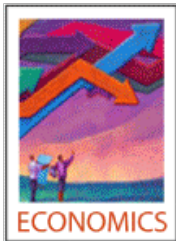
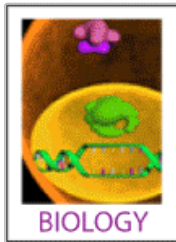
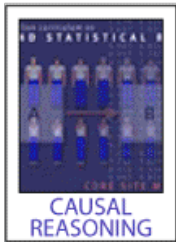
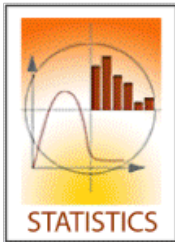
The diagram shows a red car on a grey inclined plane. The incline is labeled with a length of 20 m and an angle of 20°. A green coordinate system is centered at the bottom of the incline, with the +Y axis pointing up and the +X axis pointing right. A green dot is at the origin, with a green arrow labeled 'c' pointing down and a green arrow labeled 'd' pointing left.

Online Course

CMU: The Open Learning Initiative

www.cmu.edu/oli

- Since 2002
- 25 College courses
- Automatic data logging
- Dozens of research studies



EdX

<https://www.edx.org/>

- MIT, Harvard, Berkeley, UT
- > \$ 50 million in start-up funding
- Data collection being made public
- Data mining being prioritized

The screenshot shows the EdX website interface. At the top, there is a navigation bar with the EdX logo and links for 'HOW IT WORKS', 'COURSES', 'SCHOOLS', and 'REGISTER NOW'. A 'Log in' button is visible in the top right corner. Below the navigation bar is a banner with the text 'TAKE GREAT COURSES from the world's best colleges and universities'. Underneath the banner is a filter section for 'COURSES (86)' with options for 'all', 'new', 'current', and 'past'. There are also dropdown menus for 'all subjects' and 'all schools'. The main content area displays three course listings, each with a 'NEW' tag, a course title, a brief description, start and instructor information, and a 'learn more' button. The first course is 'BIO465X: Neuronal Dynamics - Computational Neuroscienc...', the second is 'OEE101x: Our Energetic Earth', and the third is '2.03x: Dynamics'.

Virtual Labs: Causality Lab

Causality 4.3
Exercise Help

Instructions
 Check Answer
 Show Answer
 Save
 Submit
 Essay
 Feedback

Finances
\$4,000 left

The flowchart illustrates the experimental process: **true graph** leads to **experimental setup** and **hypothesis graph**. **experimental setup** leads to **manipulated true graph**. **hypothesis graph** leads to **manipulated hyp. graph**. Both **manipulated true graph** and **manipulated hyp. graph** lead to **population**. **population** leads to **sample**, which finally leads to **predictions & results**.

Regression Analysis

Exp-Setup 1
S600 (n=600)

$$\text{BMI} = 16.874 + 0.001 \cdot \text{TV} + 1.419 \cdot \text{Par_Permissive}$$

	coeff	SE coeff	t-stats	p-value
Intercept	16.874	0.431	39.163	0.000
TV	0.001	0.002	0.275	0.784
Par_Permiss...	1.419	0.089	15.901	0.000

Regression Analysis

Exp-Setup 2
S400 (n=400)

$$\text{BMI} = 17.975 + -0.001 \cdot \text{TV}_{\text{set}} + 1.240 \cdot \text{Par_Permissive}$$

	coeff	SE coeff	t-stats	p-value
Intercept	17.975	0.631	28.487	0.000
TV	-0.001	0.002	-0.529	0.597
Par_Permiss...	1.240	0.107	11.539	0.000

Scatterplot

<BMI> vs <TV>

$$\text{BMI} = 21.817 + 0.014 \cdot \text{TV}$$

OriginalModel
Exp-Setup 1
S600 (n=600)
30.848

correlation coeff=0.263 (p=0.000)

Y-axis: BMI (15.708 to 30.848)
X-axis: TV (27.232 to 297.617)

Scatterplot

<BMI> vs <TV>

$$\text{BMI} = 23.888 + 0.001 \cdot \text{TV}_{\text{set}}$$

OriginalModel
Exp-Setup 2
S400 (n=400)
30.996

correlation coeff=0.010 (p=0.838)

Y-axis: BMI (17.201 to 30.996)
X-axis: TV (36.231 to 260.445)

UNIVERSITY OF WISCONSIN-MADISON

Virtual Labs: Chem Lab

Virtual Lab Software Interface: NYdham Chemistry Lab - Default Lab Setup

Stockroom Explorer:

- 1M NaCl
- 1M NaOH
- 1M NaCN
- 1M NaF
- 1M NaHCO_3
- 1M NaNO_2
- 1M NaNO_3
- 1M NaOCl
- 1M NaOH
- Indicators
 - Bromocresol Green
 - Cresol Red
 - Methyl Orange
 - Methyl Red
 - Phenolphthalein
- Stock Solutions
 - 11.8M HCl
 - 14.8M H_2PO_4
 - 14.8M H_2
 - 15.4M HNO_3
 - 15M HClO_4
 - 17.8M H_2SO_4

1M Sodium Hydrogen Carbonate

Workbench 1:

10mL Pipet

1M $\text{C}_2\text{H}_5\text{NH}_2$

1M NaHCO_3

log₁₀ Molarity

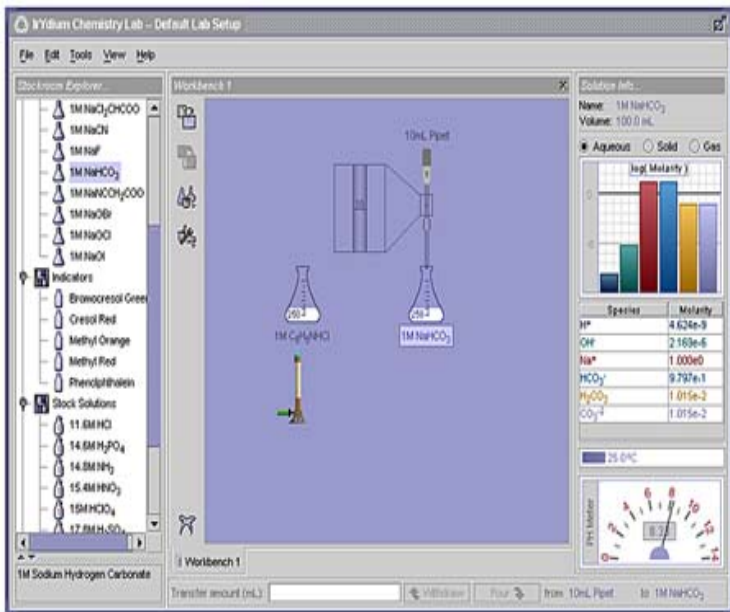
Species	Molarity
H^+	4.624e-9
OH^-	2.163e-6
Na^+	1.000e0
HCO_3^-	9.797e-1
H_2CO_3	1.015e-2
CO_3^{2-}	1.015e-2

25.0°C

pH Monitor: 8.3

Transfer amount (mL): [] Withdraw Pour from 10mL Pipet to 1M NaHCO_3

Virtual Labs: Chem Lab



- Number of engaged actions \Rightarrow 48% of the post-test variation
- # interactions with the virtual lab outweighed ALL other factors including gender and SAT score as the predictor of positive learning outcome.

Kinds of Data

1. Log data – time stamped events:
login, page request, glossary, quiz attempt, score request, video, etc

2. Assessment data -
 - Pre-test scores
 - Intermediate assessments (low stakes, high stakes)
 - Midterm score
 - Final exam scores

3. Problem Solving Data:
 - a) Unstructured Virtual Labs --> Customized Data
 - b) Structured Cognitive Tutors --> PSLC Data Shop



Log Data: Edx MOOC Example

User	Res	Time	Resp1	Resp2	Count1	Count2
9	video	2m 30s	--	--	--	--
9	answer	10m 5s	correct	correct	1	1
10	book	4m 41s	--	--	--	--
10	book	40s	--	--	--	--
10	answer	20s	incorr.	--	1	--
10	answer	15s	incorr.	--	2	--
10	answer	1m 8s	incorr.	incorr.	3	1
10	answer	28s	--	correct	--	2
10	video	2m 10s	--	--	--	--
10	answer	6s	correct	--	4	--



Log Data: Fractions Tutor Example

Student Id	Time	Duration (sec)	Student Response Type	Tutor Response Type	Problem Name	Step Name	KC Model	Attempt At Step	Outcome	Selection	Action	Input
Student1	5/14/13 14:09		1ATTEMPT							NtpDate	NtpTimeCheck	2013-05-14 10:09:23.55 1 -0400
Student1	5/14/13 14:09	32	ATTEMPT	RESULT		fract1_numMultiply1 UpdateTextArea	equivMultiplyNum	1	Correct	fract1_numMultiply1	UpdateTextArea	3
Student1	5/14/13 14:10	4	ATTEMPT	RESULT		fract1_denomMultiply1 UpdateTextArea	equivMultiplyDenom	1	Correct	fract1_denomMultiply1	UpdateTextArea	3
Student1	5/14/13 14:10	4	ATTEMPT	RESULT		_root goToStep		1	Correct	root	goToStep	2
Student1	5/14/13 14:10	18	ATTEMPT	RESULT		fract3_num UpdateTextArea	equivNameNumFract	1	Correct	fract3_num0	UpdateTextArea	1
Student1	5/14/13 14:10	3	ATTEMPT	RESULT		fract3_denom UpdateTextArea	equivNameDenomFract	1	Correct	fract3_denom0	UpdateTextArea	3
	5/14/13 14:10	6	ATTEMPT	RESULT		fract4_num UpdateTextArea	equivNameNumFract	1	Correct	fract4_num0	UpdateTextArea	3

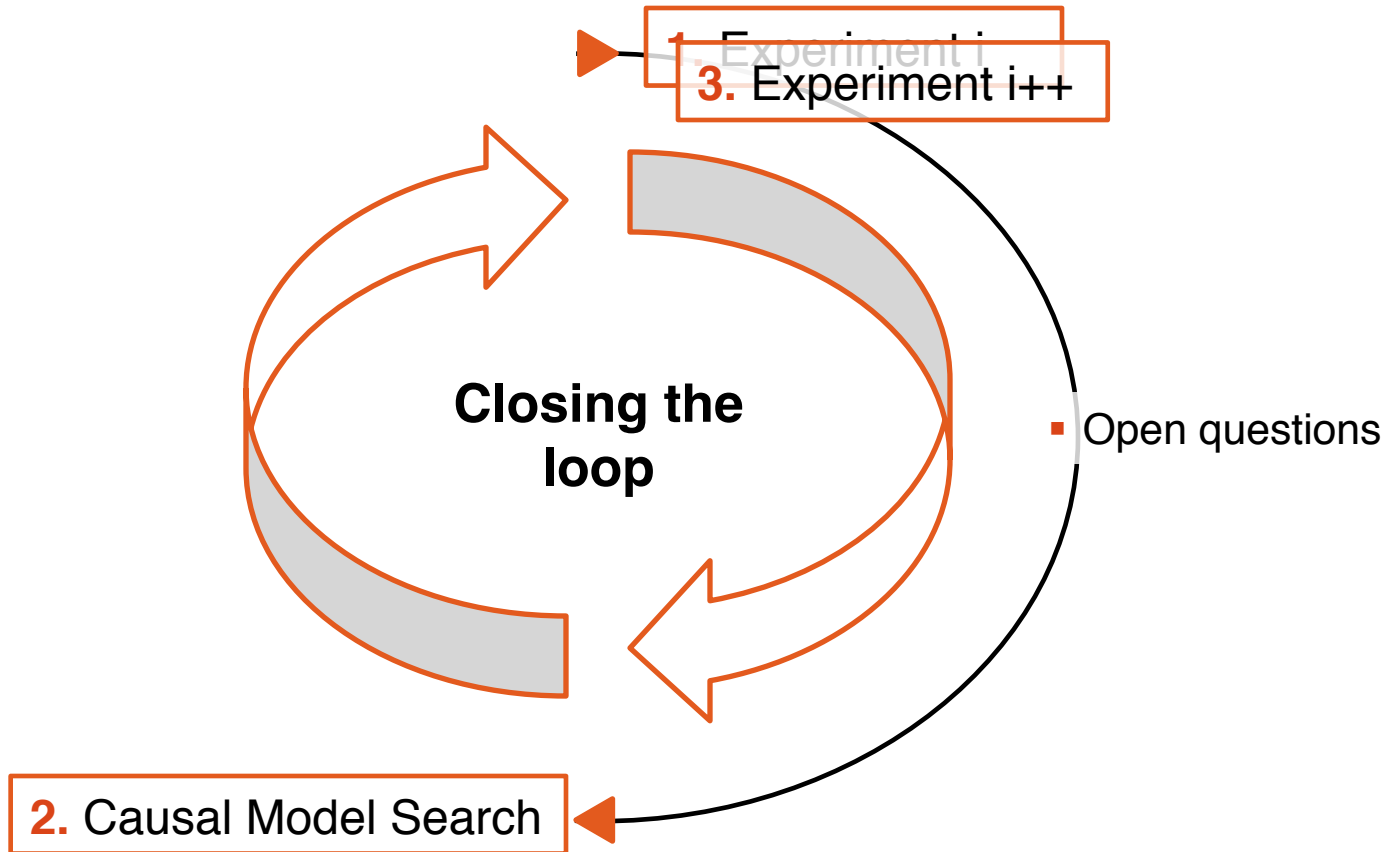
“Online” Educational Data

Questions/Challenges:

- Raw Log Data → Meaningful Variables
- Which curricular or tutorial interventions cause learning?
- Which (influencible) student behaviors facilitate learning?
- By what mechanisms do successful interventions cause learning?



Motivation



2. MODEL SEARCH: ONLINE COURSE BEHAVIORS



Causal and Statistical Reasoning

A Concrete Example: Cell Phones - Mozilla Firefox


File Edit View History Bookmarks Tools Help

https://odin.web.cmu.edu/course/workbook/a/

Calendar Philosophy Tetrad Causality Lab OLI - Course Entry ODIN OLI Blackboard NAS-VA


Suppose you are traveling in a car and you want to make several calls on your cell phone. In the simulation below, click on the "SEND" button to place a call, and click on the "END" button to end a call (you must click on END before you can try another call). The phone on the right will ring if your call got through. Attempt at least 10 calls.

SIMULATION OF CALL ATTEMPTS AND CONNECTIONS



ATTEMPTS: 1 CONNECTIONS: 1

RESET

 **Did I Get This?:**
[Click Here](#)

javascript:void openLgWin('')course/webui/resolver/link/resource.do?src=9a573ffa80020c1500bc287da28... odin.web.cmu.edu

https://odin.web.cmu.edu - Cell Phone 1 - Mozilla Firefox

File Edit View History Bookmarks Tools Help

Cell Phone 1

[Question 1](#) | [Question 2](#)

Attempt 1 for this question

Question 2

Which of the choices best represents the causal system in the simulation

- A. {Phone Button [send,end]}
- B. {Phone Button [send,end], Attempts[0,10]}
- C. {Phone Button [send,end], Call Connected [yes, no]}

Done odin.web.cmu.edu



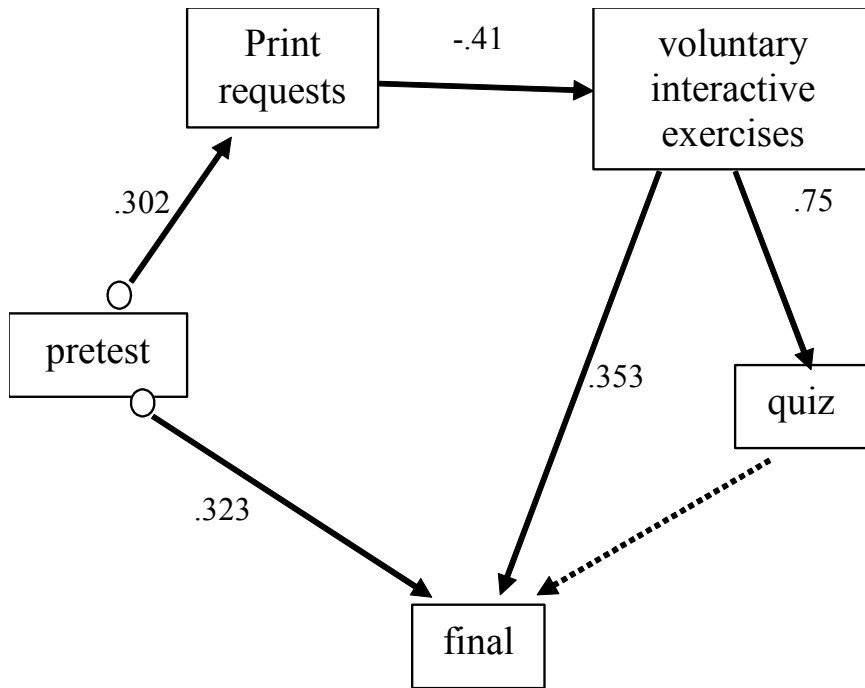
Student & Log Data

- Pre-test (%)
- Midterm1 (%)
- Gender
- Race
- Computer-comfort
- Final Exam (%)
- Logged in time
- Voluntary-exercise completion (%)
- Quiz Scores (avg. %)
- Print-requests (% of modules)
- 12 others

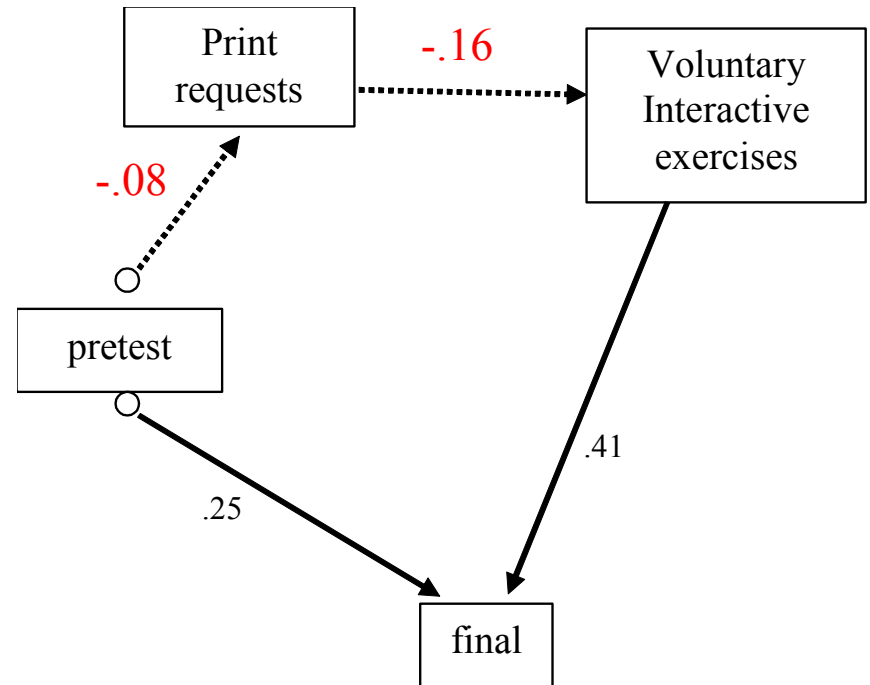


Interaction → Learning

Year 1



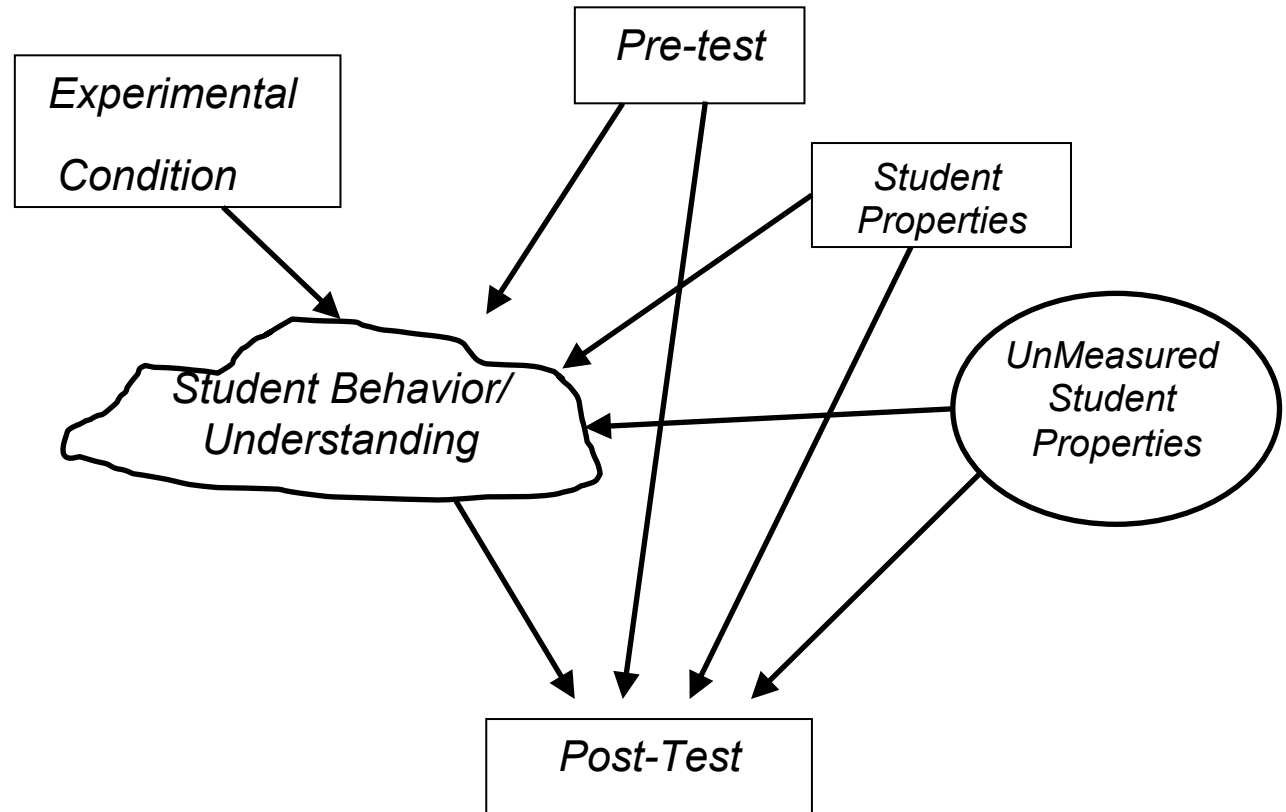
Year 2



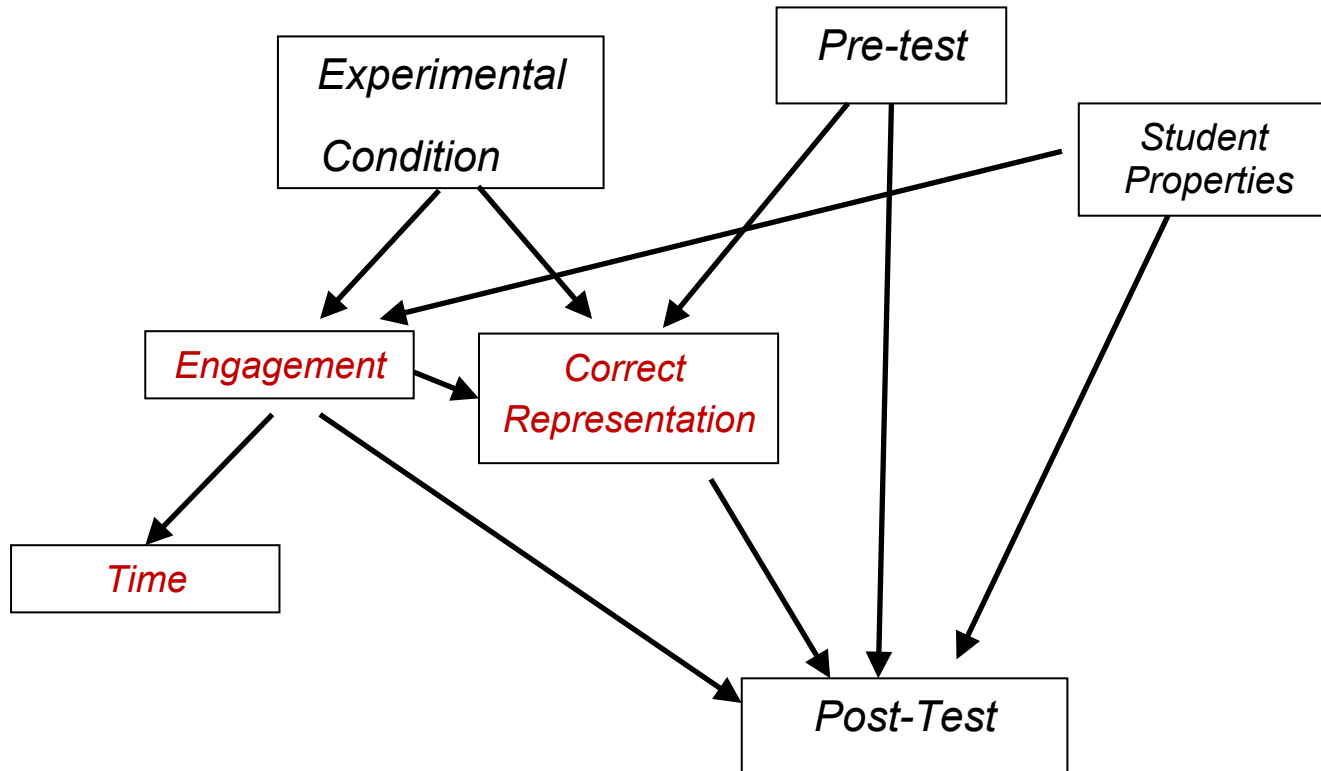
3. SEARCHING FOR MECHANISMS/MEDIATORS



What are the Mediators?



What are the Mediators?



Exp. Condition $\perp\!\!\!\perp$ Post-Test | {Pre-test, Student Properties, Engagement, Correct Rep}

Exp. Condition $\not\perp\!\!\!\perp$ Post-Test | {Pre-test, Student Properties, Time, Correct Rep}

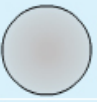



Fractions Tutor

Naming Fractions

A Let's name a fraction to compare it to another!

This is the **unit** of the fraction shown below. Let's find the **fraction** of the blue sections.



1  How many **blue sections** are there?


2 Use the arrows to make all sections the same size.


3 How many blue sections do you need to **fill** the gray diagram?

4 What fraction are the blue sections of the **unit**?

B Let's name a second fraction to compare it to the first!

This is the **unit** of the fraction shown below. Let's find the **fraction** of the purple sections.



1  How many **purple sections** are there?

2 Use the arrows to make all sections the same size.

3 How many purple sections do you need to **fill** the gray diagram?

4 What fraction are the purple sections of the **unit**?

C Are these fractions still the same?

1 How many **total sections** are in the blue diagram?
How many **total sections** are in the purple diagram?

2 The blue sections are the purple section.


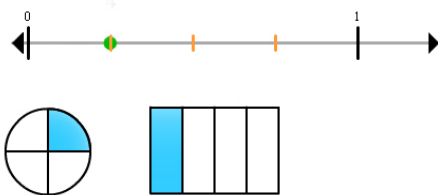
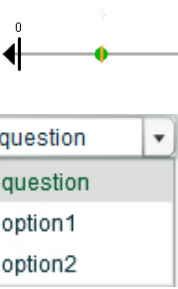
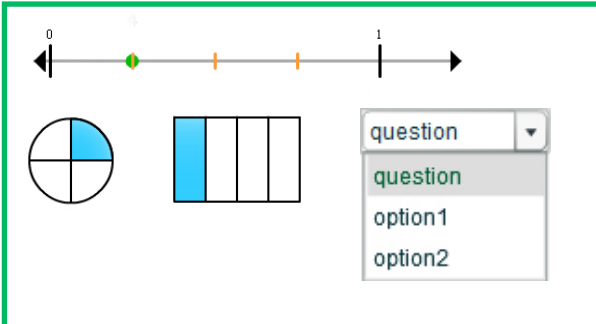
3 However, the diagrams show fractions, because their **units** have shapes.

?
Hint

continue




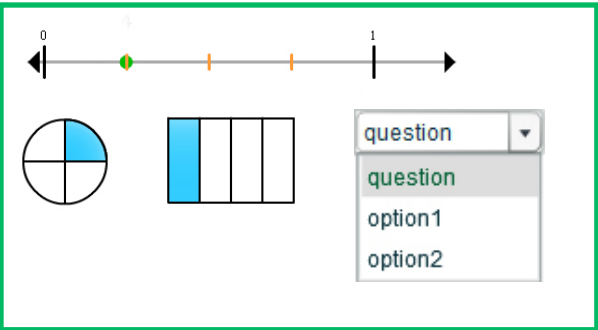
Wonderful!

Experiment 1

	Single graphical representation	Multiple graphical representations
No self-explanation prompts		
Self-explanation prompts		

$N = 110$ 6th-grade students, 2.5h
[Rau et al., AIED 2009, best student paper]

Experiment 2

	Single graphical representation			Multiple graphical representations
Self-explanation prompts	 <input type="text" value="question"/> question option1 option2	 <input type="text" value="question"/> question option1 option2	 <input type="text" value="question"/> question option1 option2	

$N = 290$ 4th- and 5th-grade students, 5h
[Rau et al., ICLS 2012]

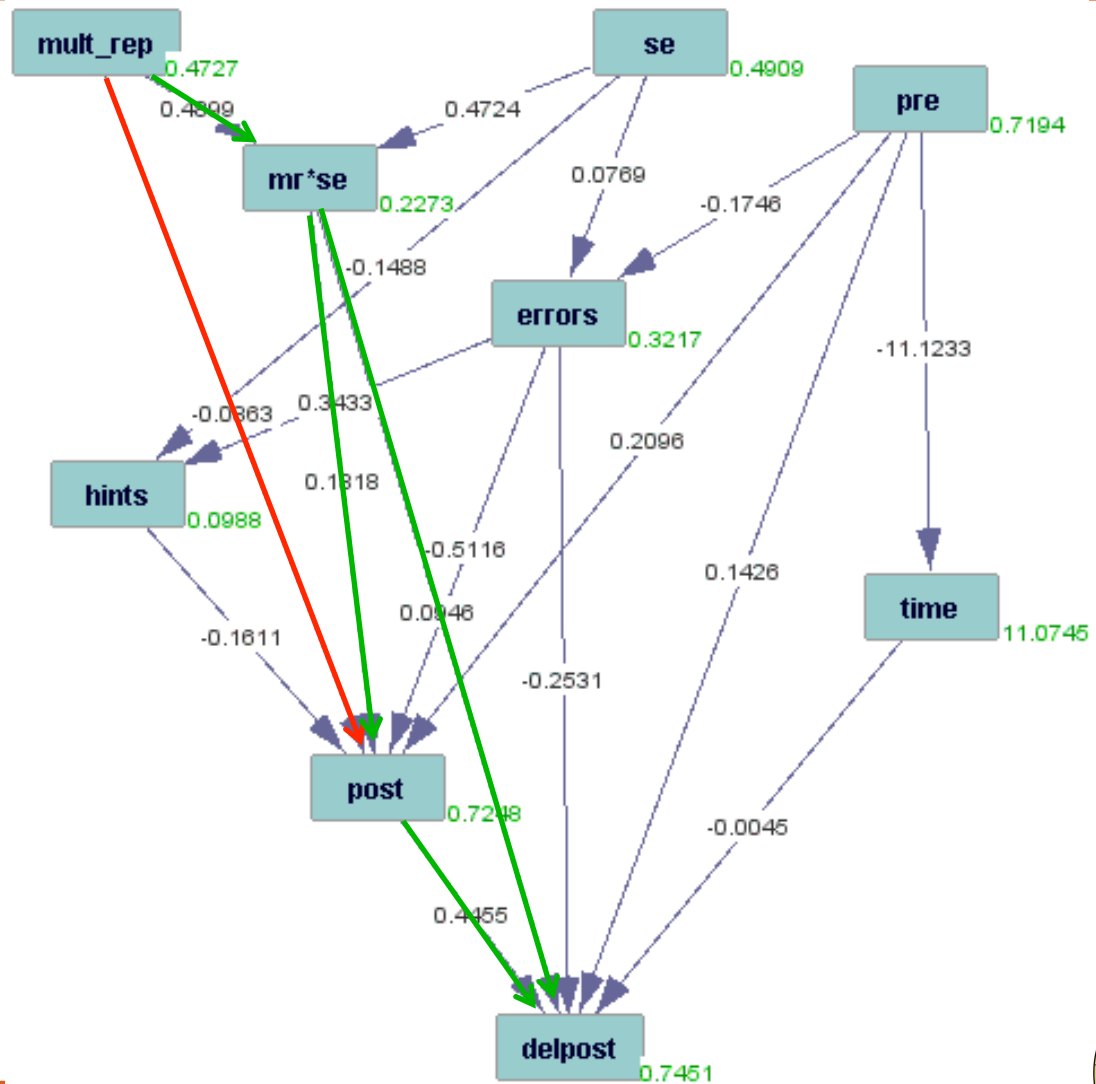
Learning with Multiple Representations

- Multiple representations \Rightarrow Learning ✓
- Mechanisms?
- Standard in ITS (Intelligent Tutor Systems):
 - *Error-rate*
 - *Hint-use*
 - *Time-spent*



Model Search: Experiment 1

No mediation of multiple representations on learning



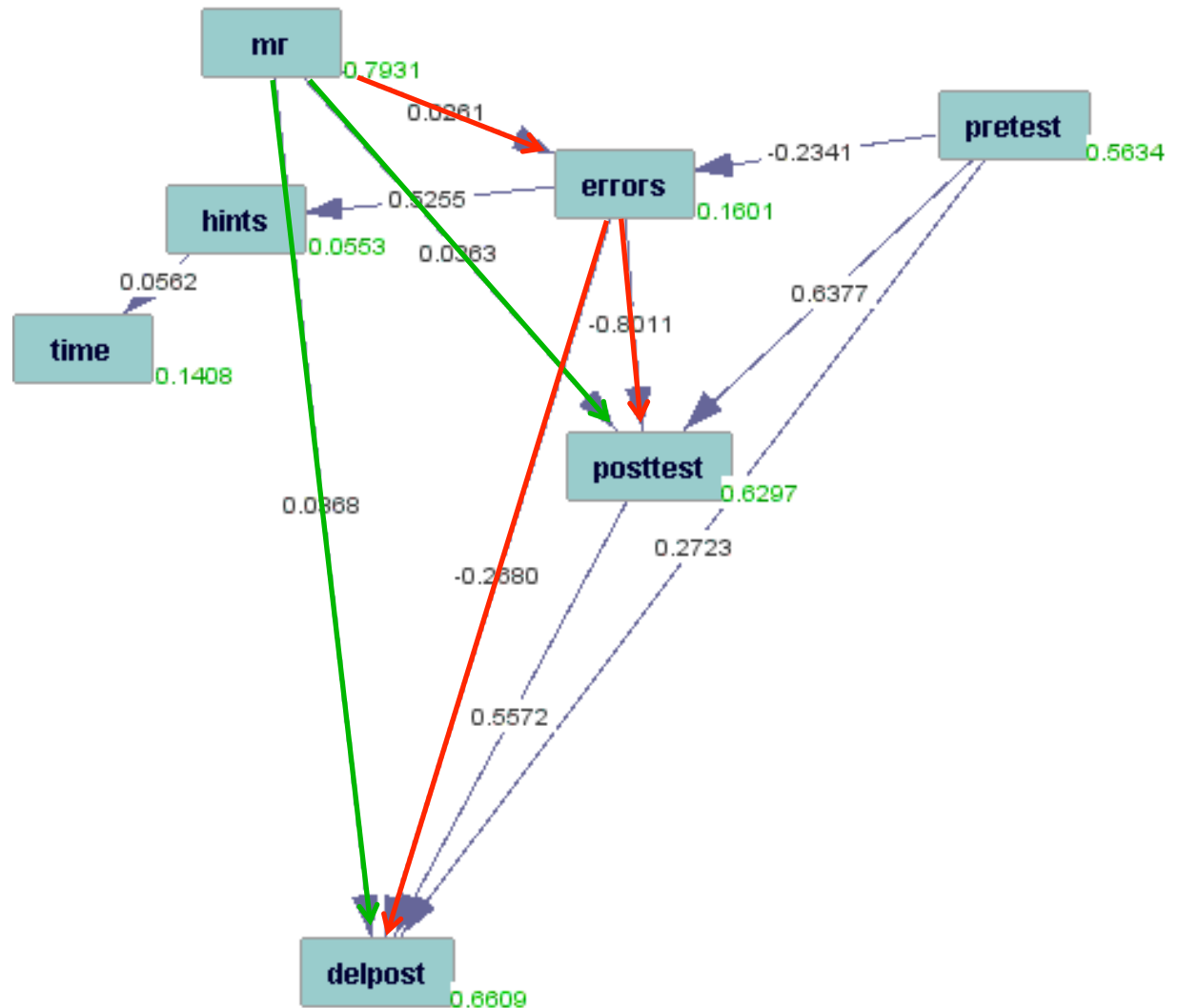
$$\chi^2_{25} = 22.11, df = 19, p = .29$$



Model Search: Experiment 2

Error-rate
mediates **negative**
effect

Positive direct
effects

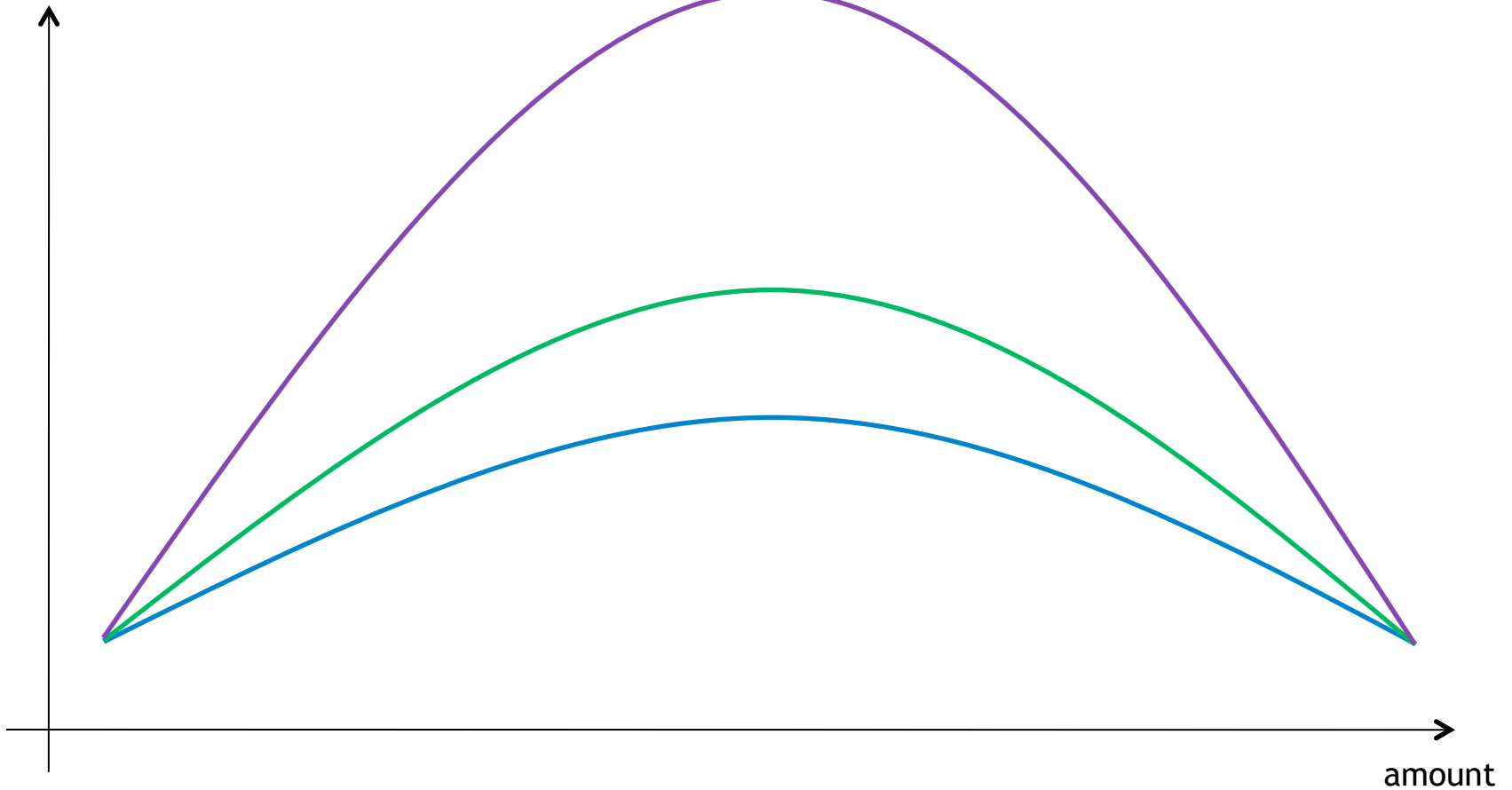


$$\chi^2 = 6.89, df = 10, p = .74$$

Mediator Variables: Non-monotonic?

- time-spent
- error-rate
- hint-use

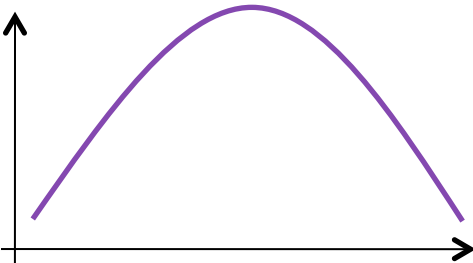
learning gains



27

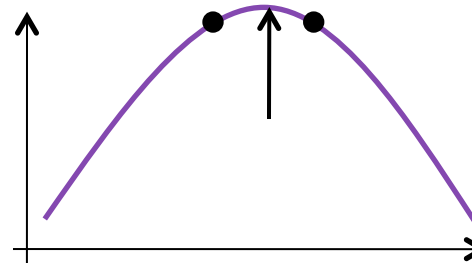
Transforming/Defining Variables

Raw data
(non-monotonic)



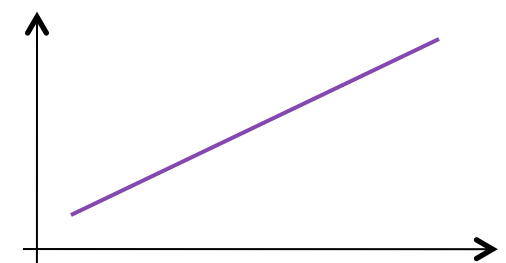
Raw measures of
error-rate, hint-
use, time-spent,

Transformation



Identification of
'optimal level' of
error-rate, hint-
use, time-spent

Transformed Var.
(monotonic)



transformation:
distance (squared
distance) from
optimum

Transforming Variables: No help

- Result: raw variables no worse, perhaps better
- Models using the raw variables explained slightly more variance than models with the transformed variables

[Rau & Scheines, EDM 2012]

Experiments 1&2 Conclusions

- Multiple representations increase learning
- Standard Variables: *Time*, *Error*, and *Hints* do ***not*** seem to be mechanisms through which multiple representations *increase* learning

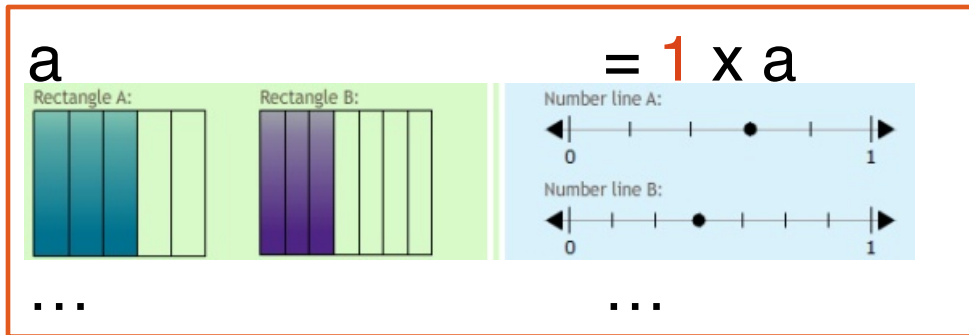


4. INFORMED MEDIATORS

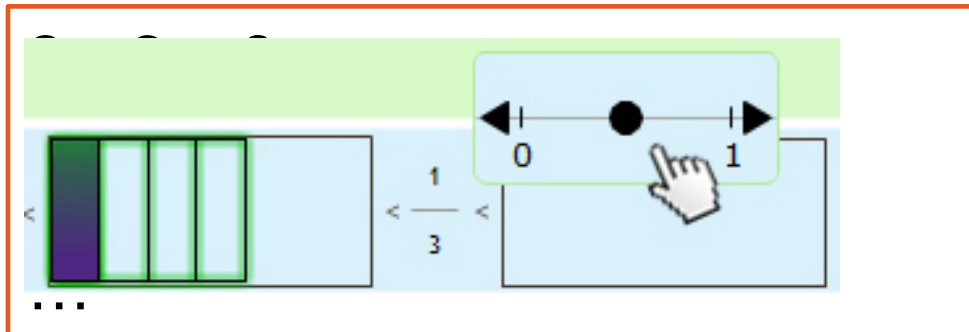


Motivation

- Learning processes [Koedinger et al., 2012]:
 - **Understanding**: sense-making processes



- **Fluency**: fluency-building processes

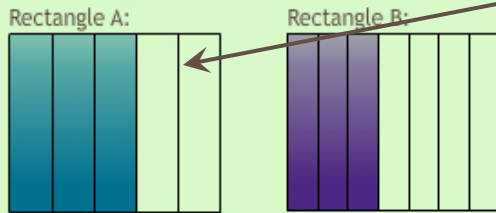


Fractions Tutor: Sense-making

Comparing Fractions

A Let's review a rectangle as an example to compare two fractions!

1 The two rectangles below show $\frac{3}{5}$ and $\frac{3}{7}$.



2 The sections in rectangle A are **larger than** the sections in rectangle B, because in rectangle A, there are **fewer** sections than in rectangle B.

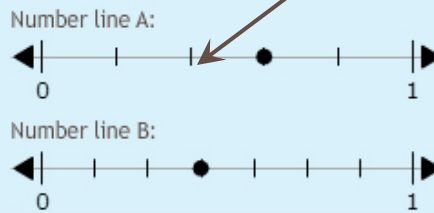
3 Since there are **3** colored sections, in each rectangle, the fraction in rectangle A is **larger than** the fraction in rectangle B.

C What did we learn about the rectangle and the number line?

1 Rectangle A and number line A each have **5** total sections. Rectangle B and number line B each have **7** total sections.

B Let's use a number line to compare two fractions!

1 The two number lines below show $\frac{3}{5}$ and $\frac{3}{7}$.



2 The sections in number line A are **larger than** the sections in number line B, because in number line A, there are **fewer** sections than in number line B.

3 Since there are **3** sections between 0 and the dot in each number line, the fraction in number line A is **larger than** the fraction in number line B.

2 The **more** sections the rectangle and the number line are cut into, the **smaller** the size of the sections.

3 All rectangles and number lines with the same numerator, so the rectangle with the **larger** sections shows the **larger** fraction.

How do these representations relate?

← Previous Next →

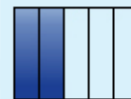
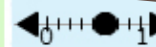
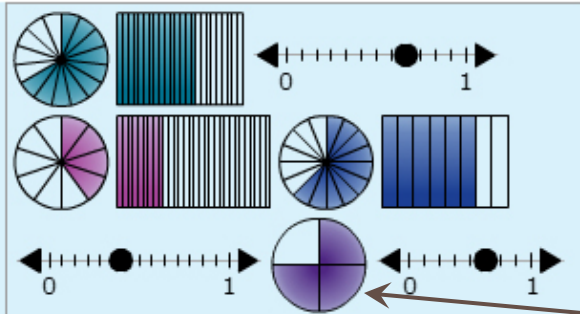


Fractions Tutor: Fluency-building

Mixed Shapes

Let's look at different shapes of fractions to sort them!

Which of these shapes show equivalent fractions?
Don't count the sections, try to judge the size of the fractions *visually*.



Which representations are equivalent?



Background: Experiment 3

		Sense-making problems	
		no	yes
Fluency-building problems	no		
	yes		
Control			

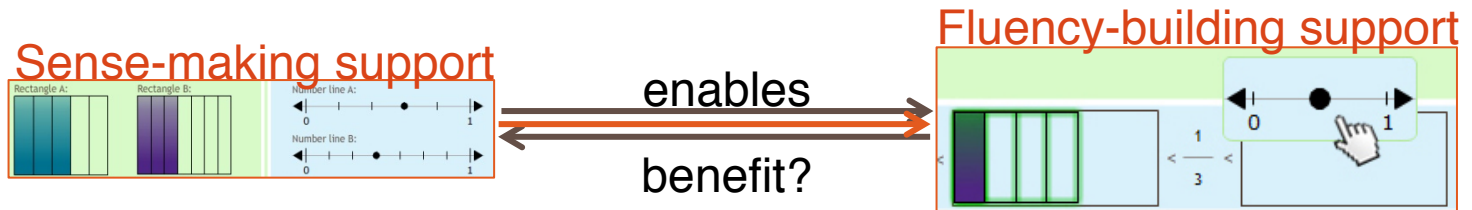
■ $N = 599$ 4th-/5th-graders

[Rau et al., ITS 2012]



Mediator hypotheses

- How do sense-making processes and fluency-building processes interact?
 - Understanding hypothesis:



Mediation hypothesis

sense + fluency
(vs. fluency-only)
(vs. sense-only)

Mediators

Performance on
fluency-problems

Performance on
sense-problems

pre

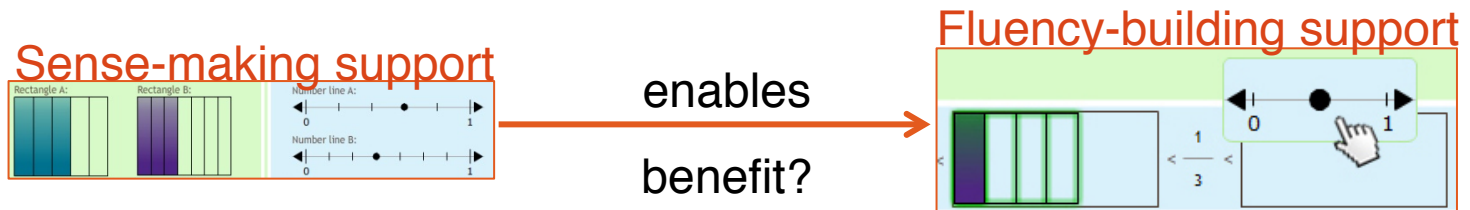
post

delayed

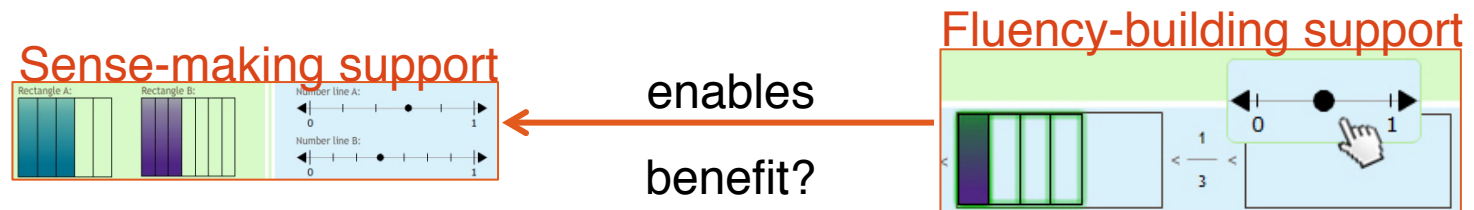


Mediation Hypotheses

- How do sense-making processes and fluency-building processes interact?
 - Understanding hypothesis:



- Fluency hypothesis:



Mediation Hypotheses

sense + fluency
(vs. fluency-only)
(vs. sense-only)

Mediators
Performance on
fluency-problems

Mediators
Performance on
sense-problems

pre

post

delayed



Variable identification

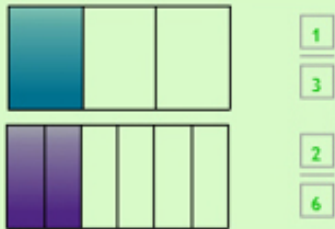
- Search among large number of potential variables
[Rau et al., EDM 2012]
- Based on knowledge component model



Knowledge Component Model

Equivalent Fractions

A Let's review rectangles to see what makes fractions equivalent!



1 The blue and the purple rectangle show **different** fractions. What **fraction** does each rectangle show?

2 Are these two fractions **equivalent**?

3 $\frac{1}{3} = \frac{1 \times 2}{3 \times 2} = \frac{2}{6}$ By what numbers must you **multiply** to get the **equivalent** fraction?

B Let's use number lines to see what makes fractions equivalent!



1 The two number lines show **different** fractions. What **fraction** does each number line show?

2 Are these two fractions **equivalent**?

3 $\frac{1}{2} = \frac{1 \times 2}{2 \times 2} = \frac{2}{4}$ By what numbers must you **multiply** to get the **equivalent** fraction?

C What did we learn about the rectangle and the number line?

1 You can find **equivalent** fractions by **multiplying** numerator and denominator by number.

2 **Multiplying** the numerator and the denominator by the **same number** is like **cutting** the areas into more sections changing the **amount**.

3 Rectangles and number lines that show the amount with numbers of sections show **equivalent** fractions.

equivNameNumFract

equivNameDenomFract

equivFractEquivalent

equivMultiply

relationEquivSameAmount

relationEquivDiffNumbers

relationEquivMultiplySameNumber

Variable identification

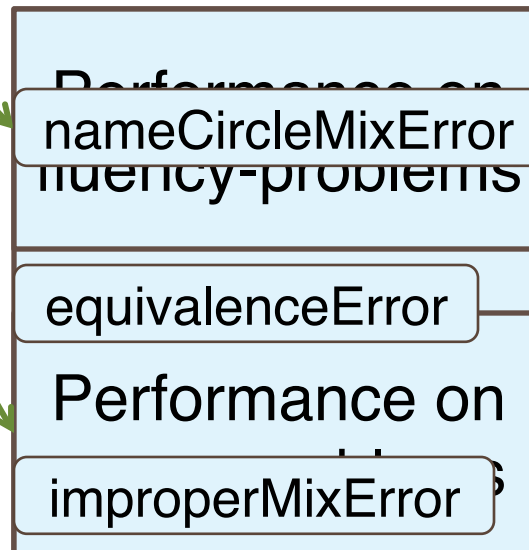
- Search among large number of potential variables
[Rau et al., EDM 2012]
- Based on knowledge component model
 - Significant predictors of posttest performance
 - Significant differences between conditions



Mediation hypothesis

sense + fluency
(vs. fluency-only)
(vs. sense-only)

Mediators



pre

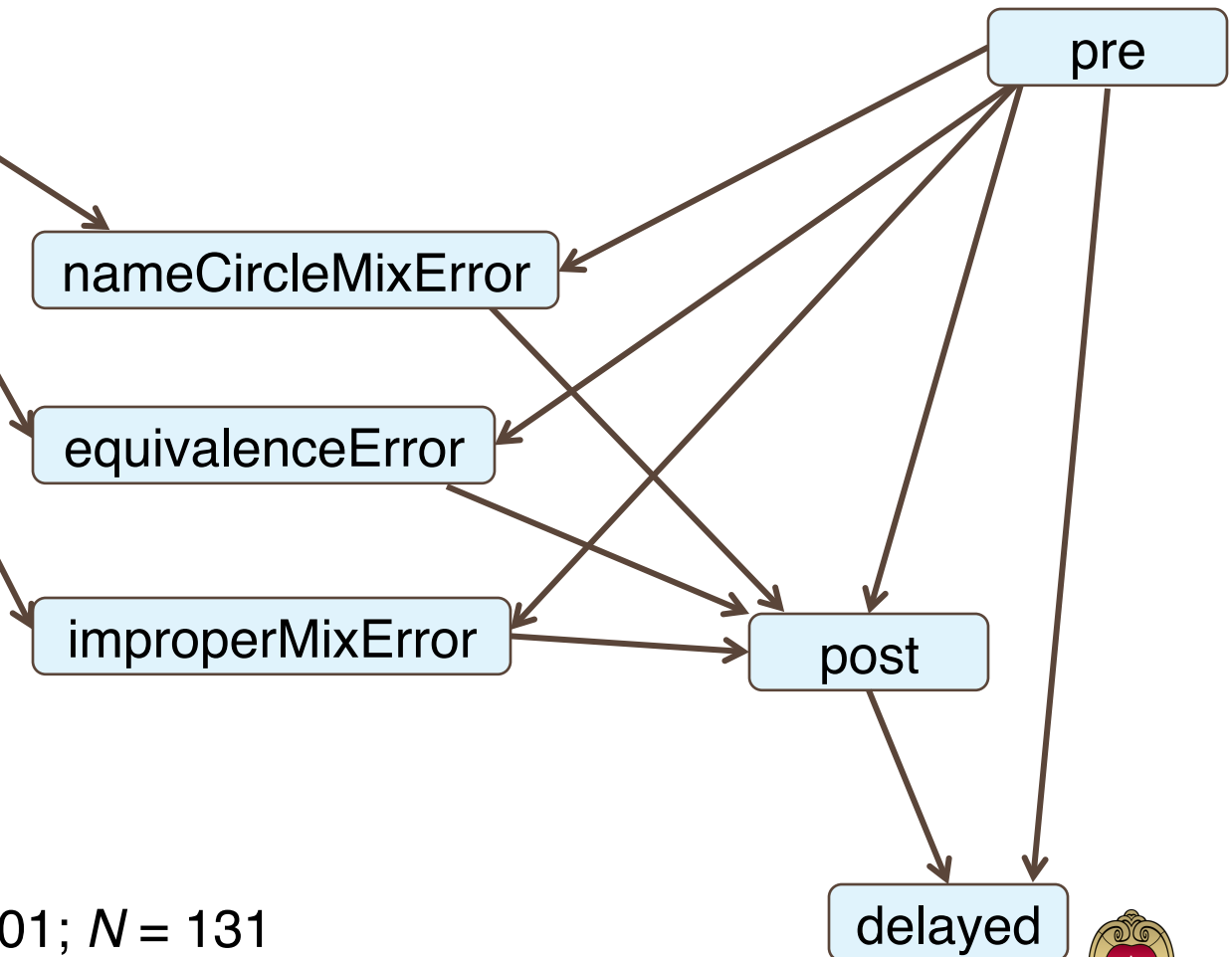
post

delayed



Understanding hypothesis

sense + fluency
(vs. fluency-only)
(vs. sense-only)

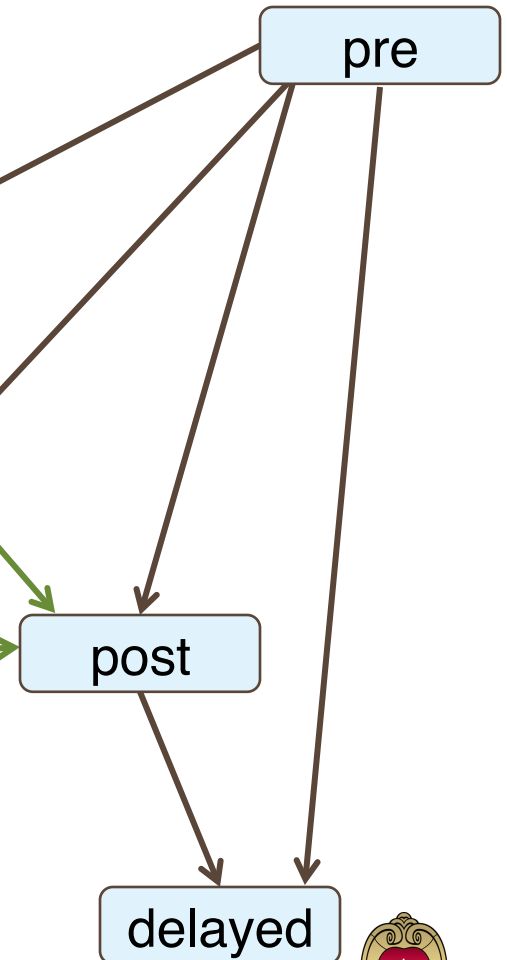
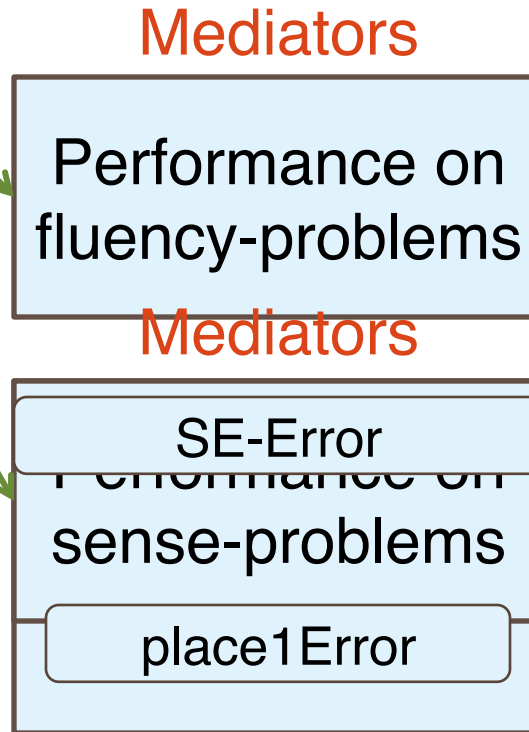


$\chi^2 = 30.88$, $df = 9$, $p < .0001$; $N = 131$



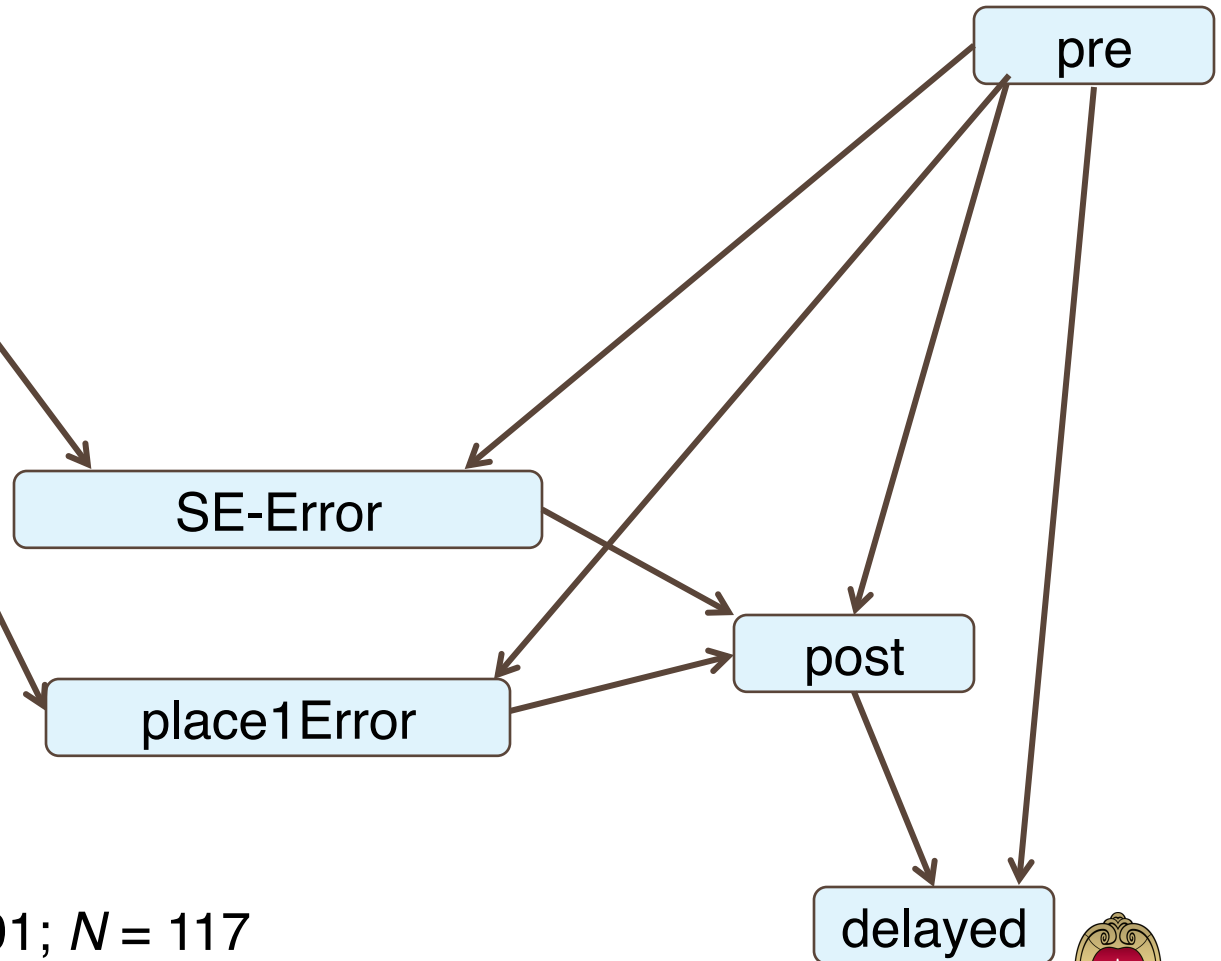
Fluency hypothesis

sense + fluency
(vs. fluency-only)
(vs. sense-only)



Fluency hypothesis

sense + fluency
(vs. fluency-only)
(vs. sense-only)



$\chi^2 = 49.14, df = 6, p < .0001; N = 117$



Possible alternative models

sense + fluency
(vs. fluency-only)
(vs. sense-only)

nameCircleMixError

equivalenceError

improperMixError

pre

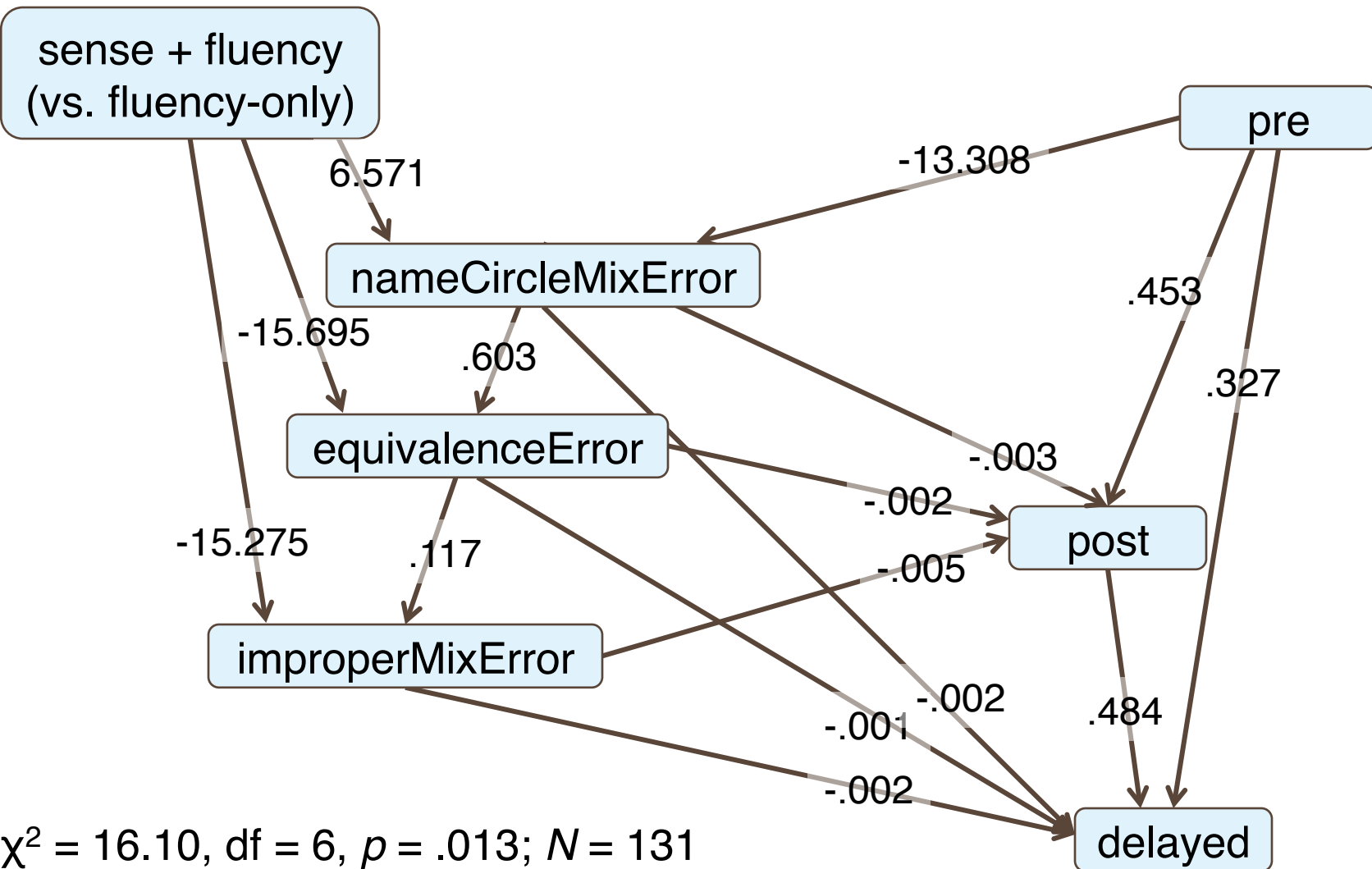
post

delayed

Possibilities: $> 2^{20}$

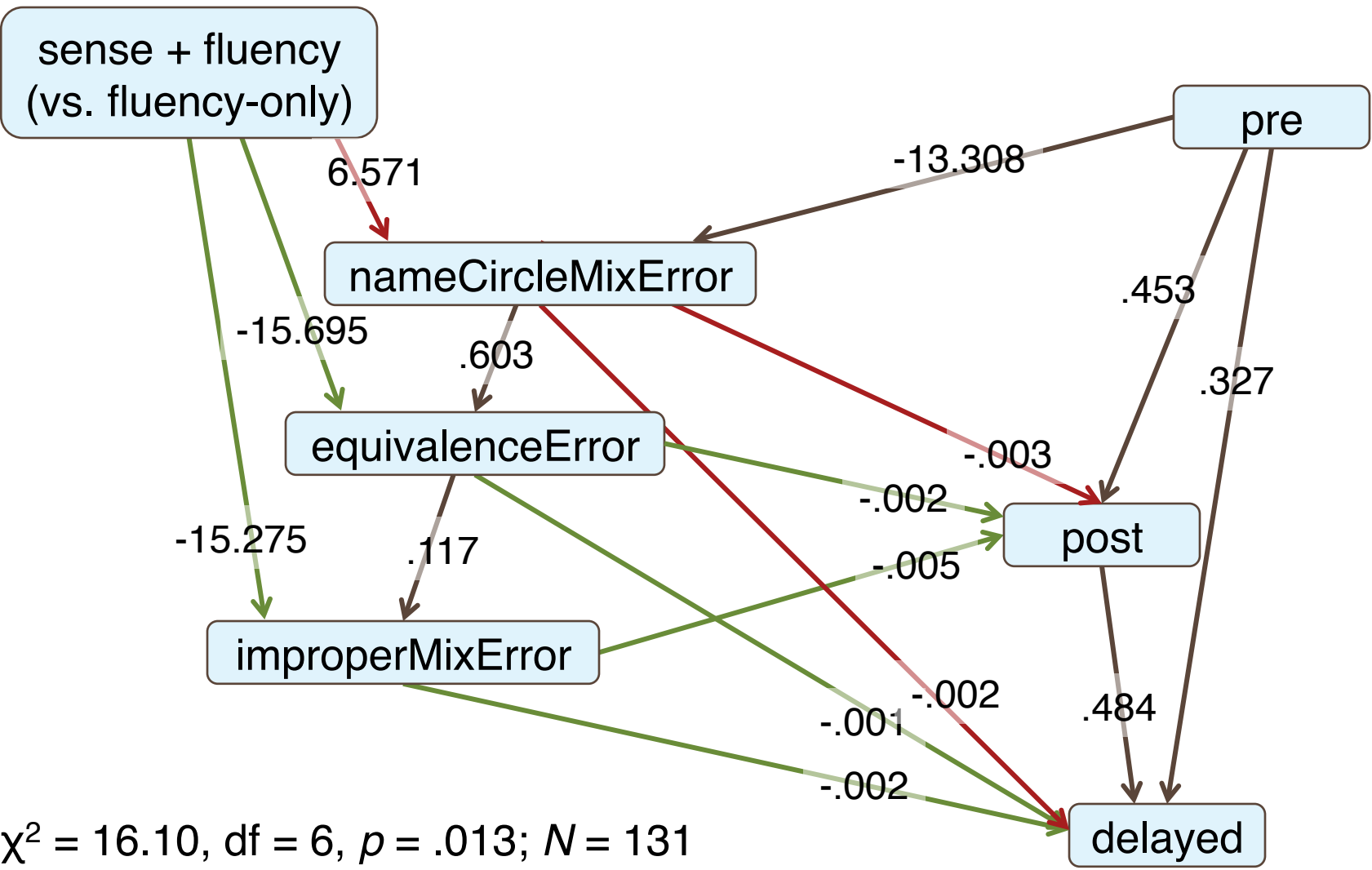


Model Search Results: Understanding model



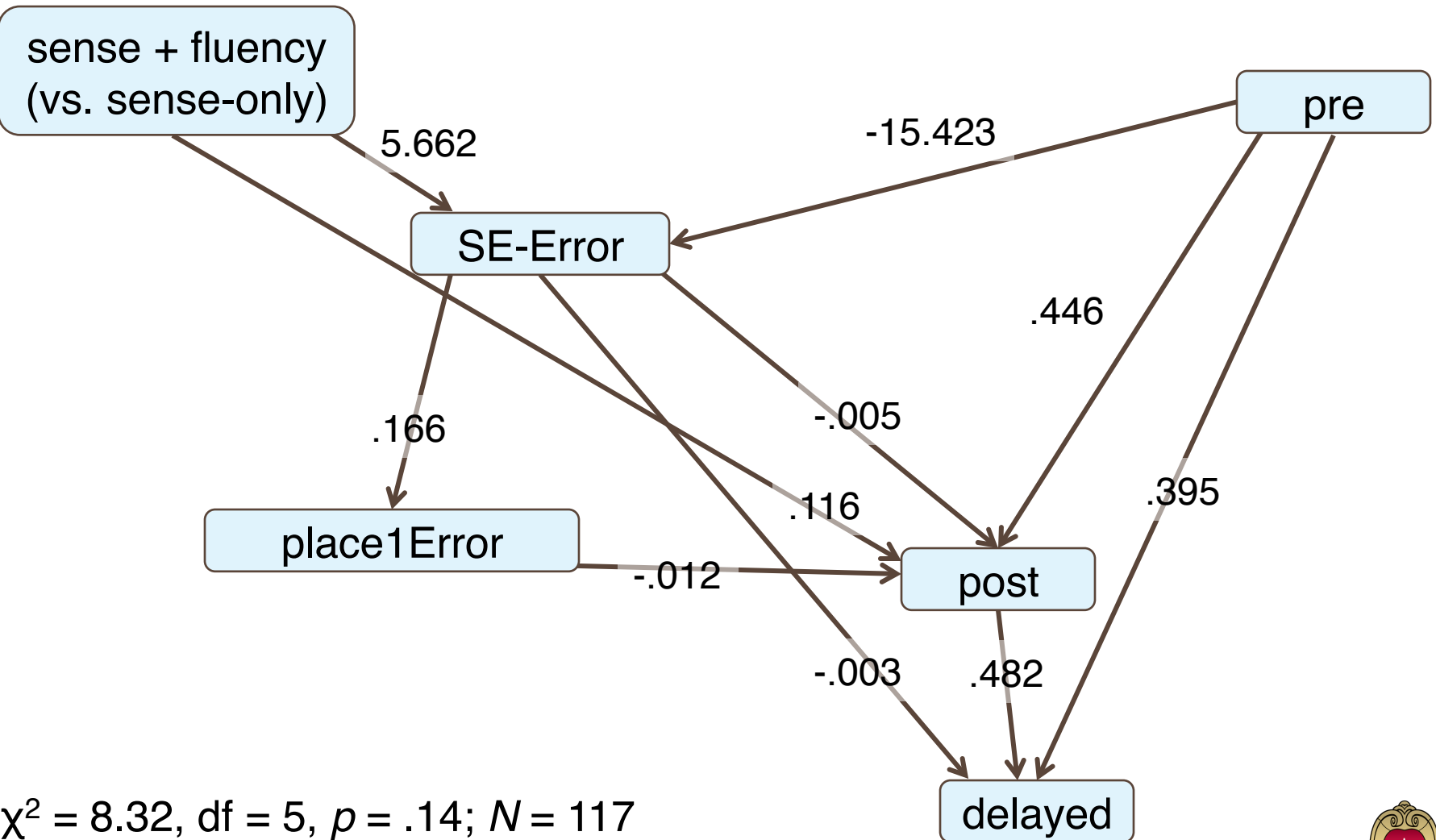
$\chi^2 = 16.10, df = 6, p = .013; N = 131$

Model Search Results: Understanding model



$\chi^2 = 16.10, df = 6, p = .013; N = 131$

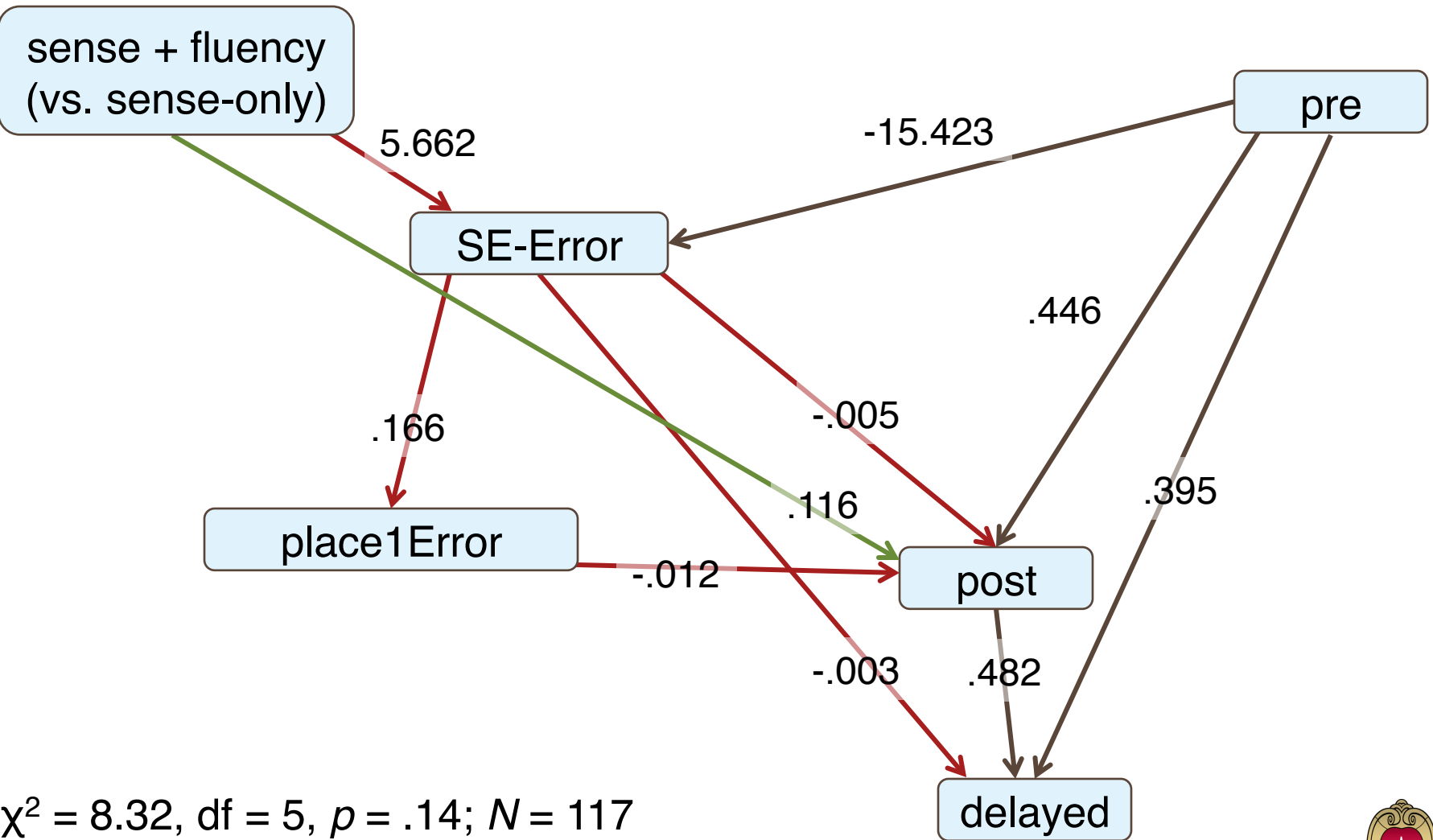
Model Search Results: Fluency model



$\chi^2 = 8.32$, $df = 5$, $p = .14$; $N = 117$



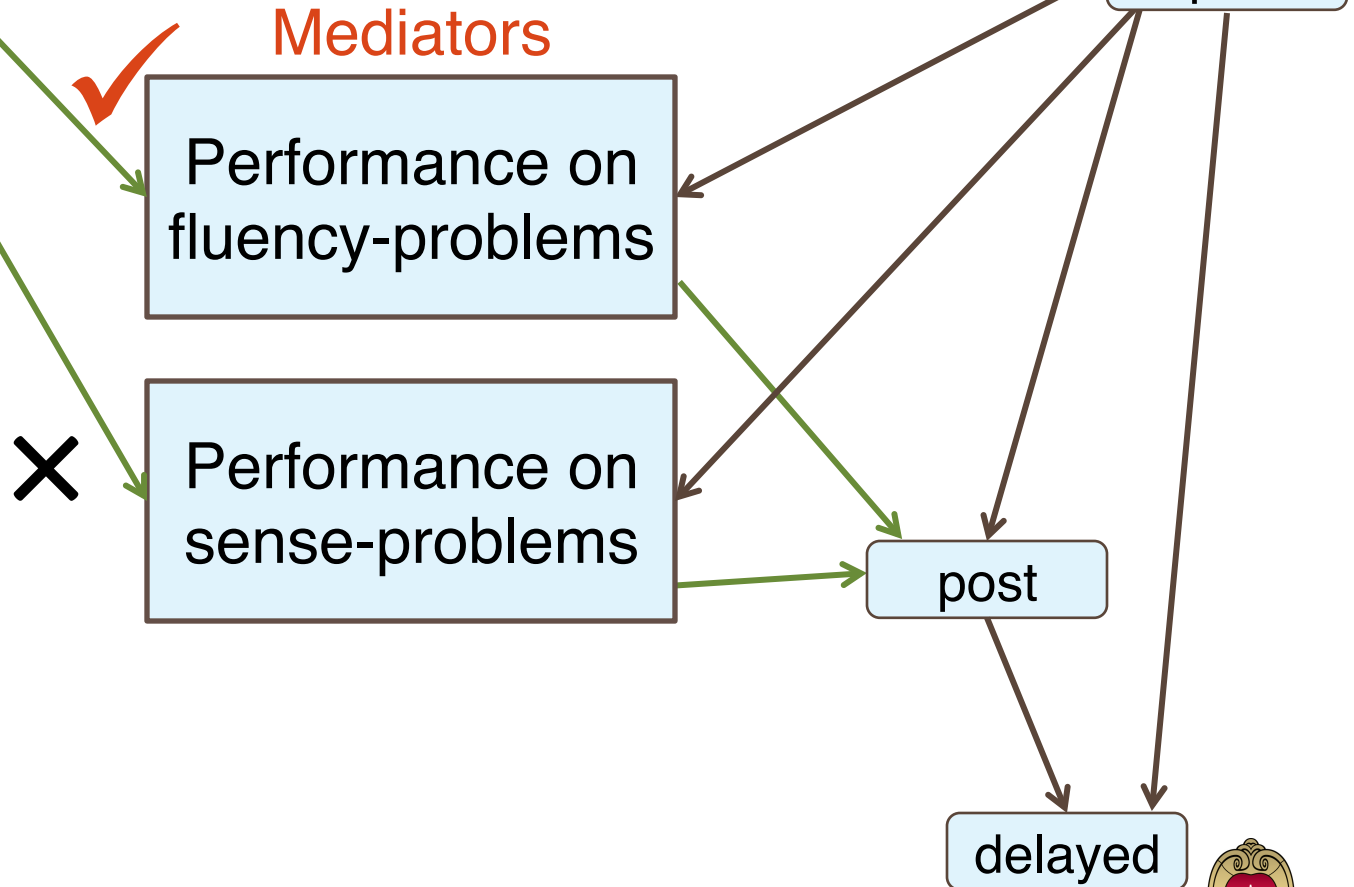
Model Search Results: Fluency model



$\chi^2 = 8.32, df = 5, p = .14; N = 117$

Mediation hypothesis

sense + fluency
(vs. fluency-only)
(vs. sense-only)



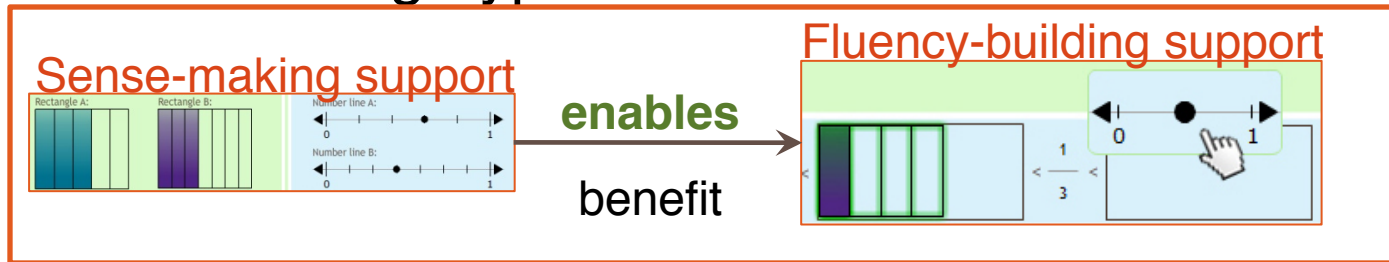
Taking Stock

- Results are in line with understanding hypothesis, but not with fluency hypothesis
 - Sense-making support reduces errors students make on fluency-building problems
[Rau, Scheines et al., EDM 2013, best paper]
- Limitations
 - Bound to fixed sequence: sense – fluency
 - Different results possible with sequence fluency – sense
- Makes testable predictions:
 - Sense-making support should be provided *before* fluency-building support

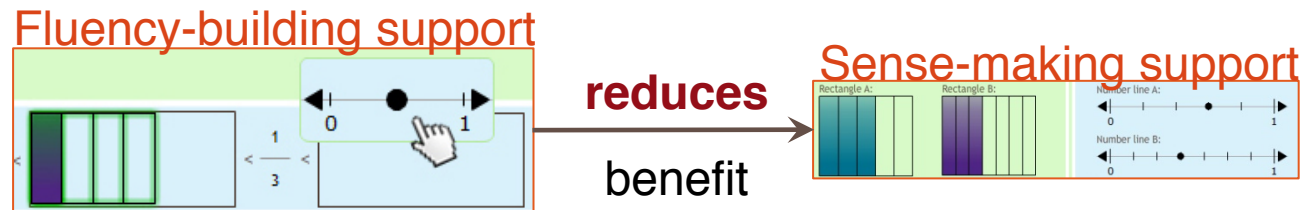
Experiment 4: Results

- Which process should instruction support first?

- Understanding hypothesis:



- Fluency hypothesis:

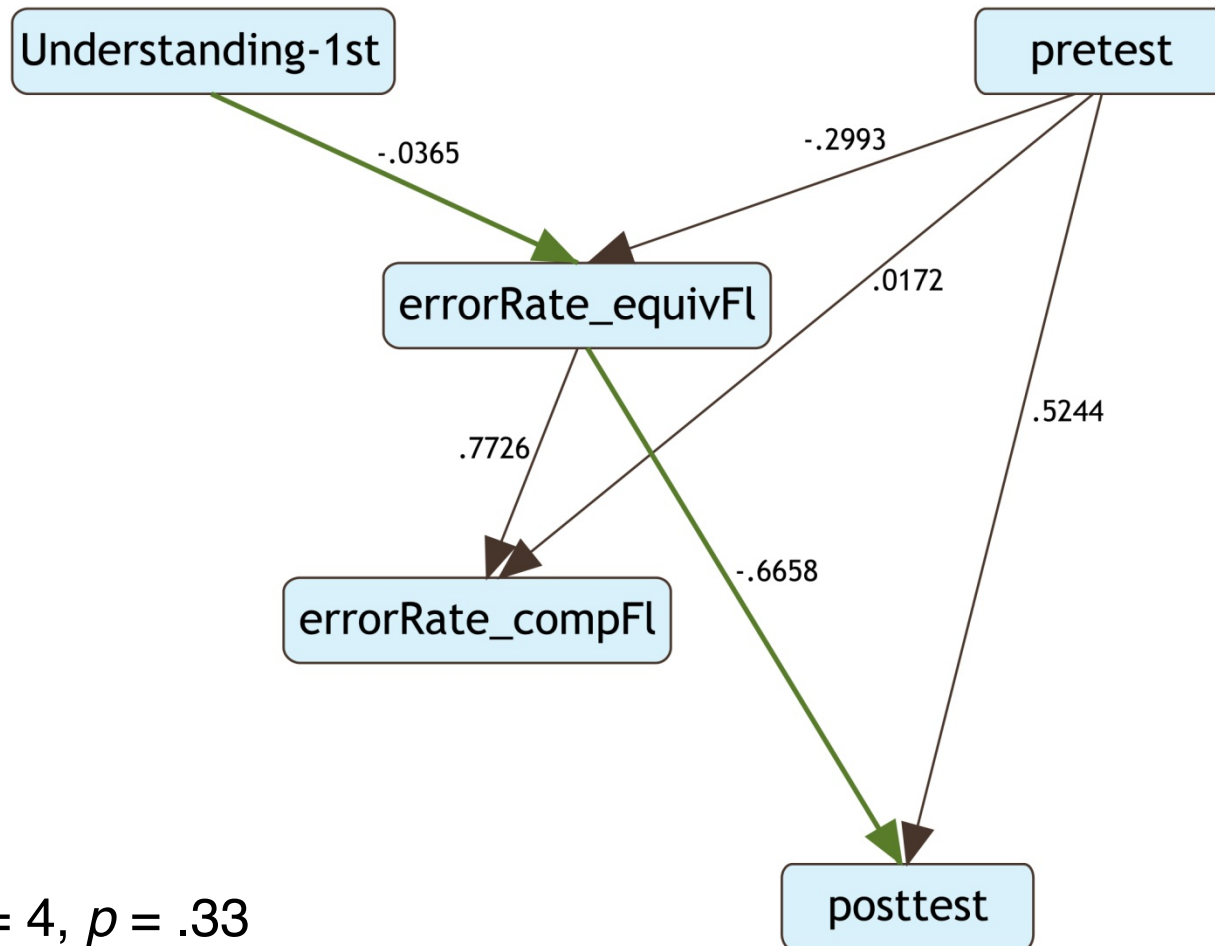


[Rau et al., AIED 2013]



Experiment 4: Model Search Results

Fluency-building errors

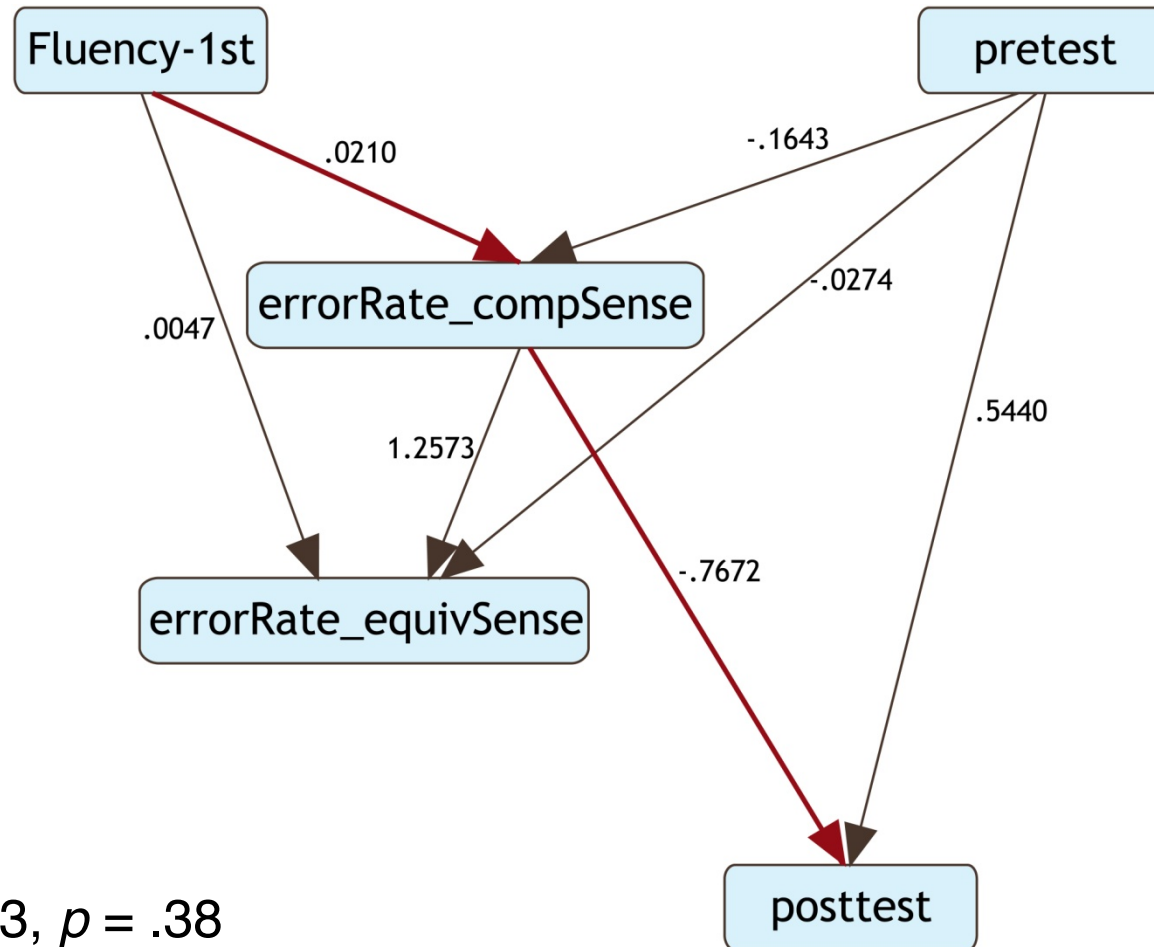


$\chi^2 = 4.58, df = 4, p = .33$



Experiment 4: Model Search Results

Sense-making errors



$\chi^2 = 3.38$, $df = 3$, $p = .38$



5. CONCLUSION



Conclusion

- Both sense-making processes and fluency-building processes need to be supported
- Sense-making enhances fluency-building
- Sense-making support should be provided before fluency-building support
- Closing the loop!

1. Experiment 3

2. Causal path analysis

3. Experiment 4



Conclusion

- Overall measures of problem-solving behaviors were not successful at establishing mediation
- Informed mediators explained interaction between different learning processes
- Model search helped identify plausible models for our hypotheses
- Results from mediation analysis made testable predictions
- Results from follow-up experiment were in line with these predictions



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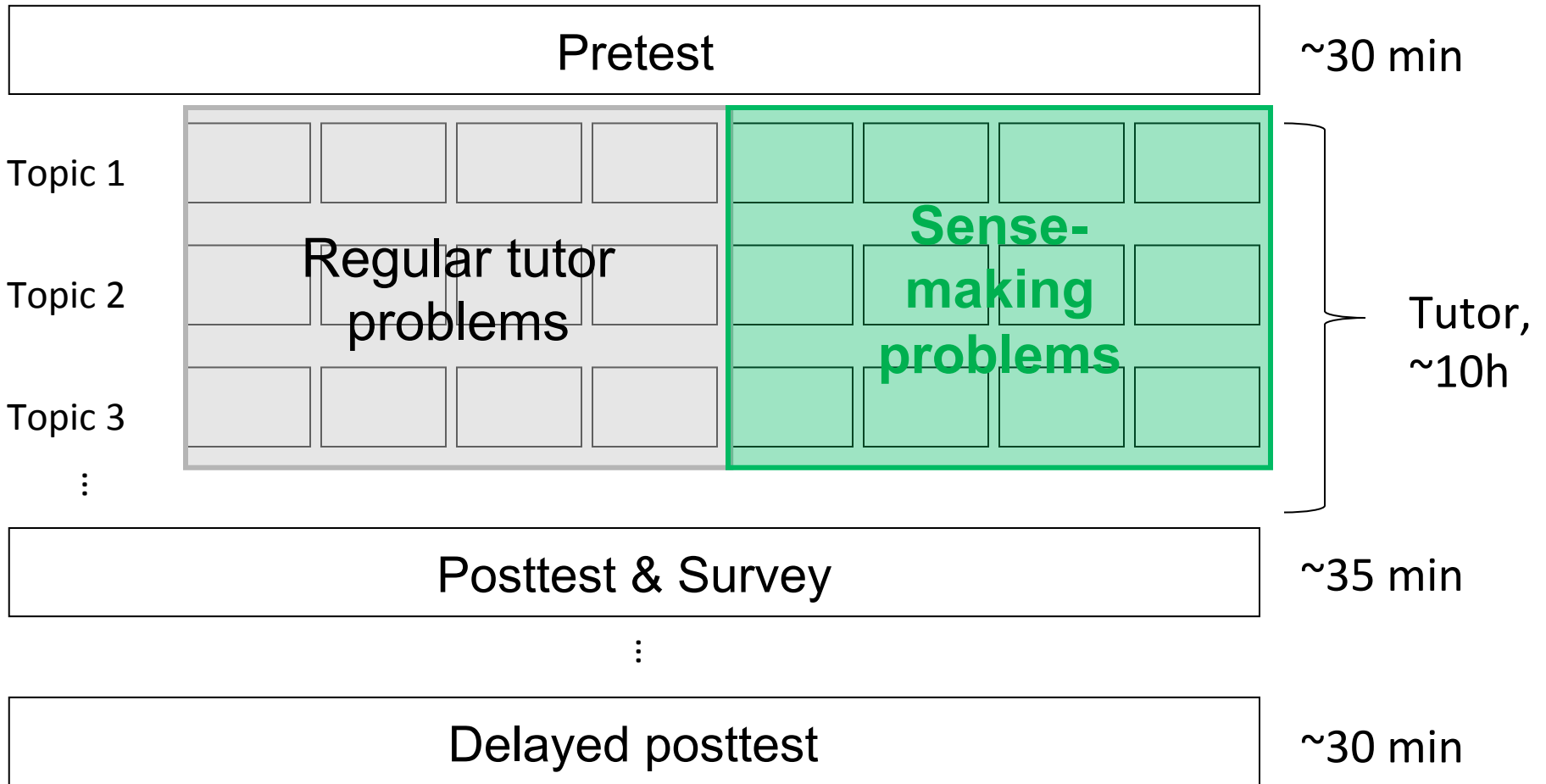
Students and teachers who have participated in my research



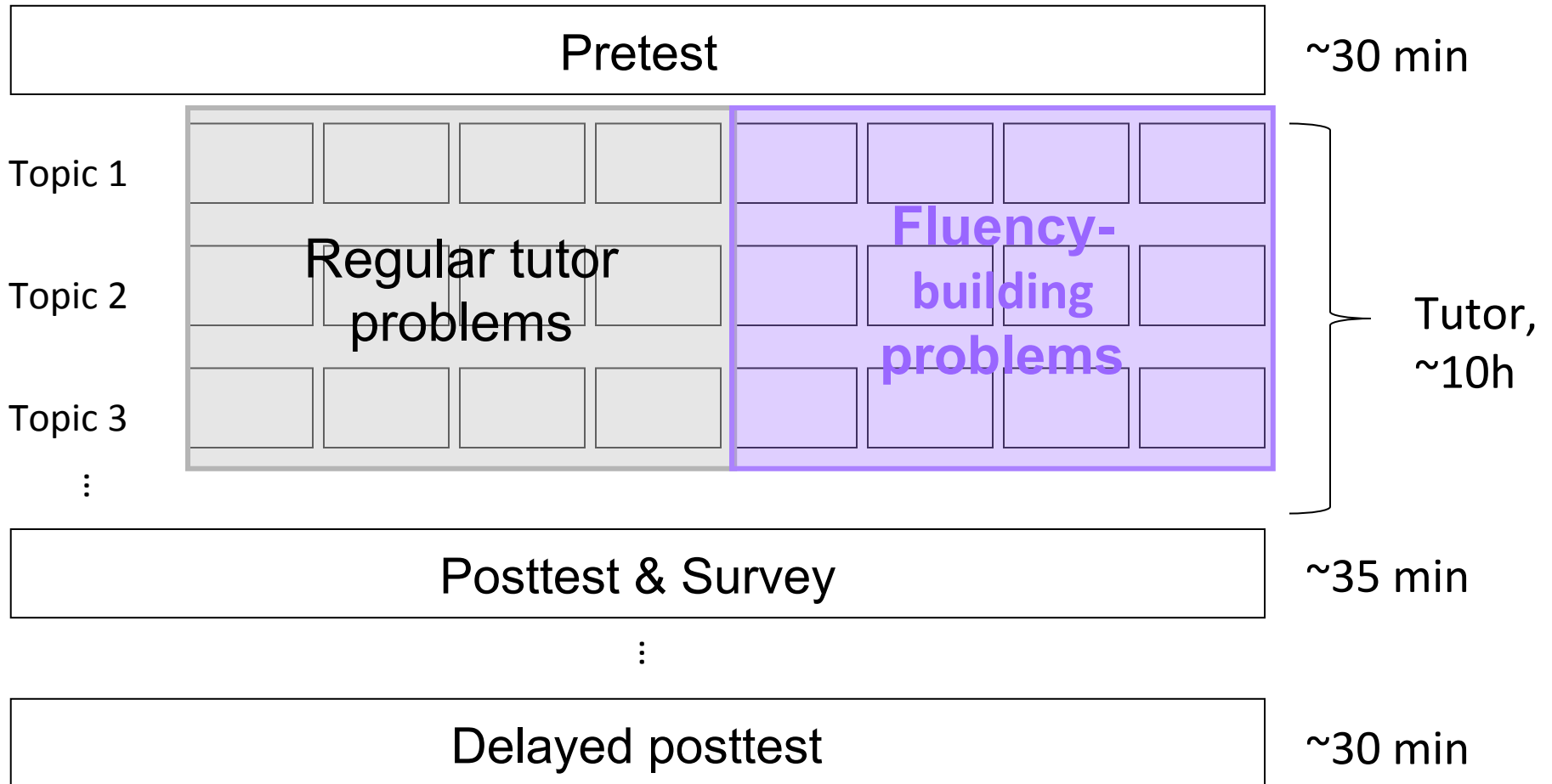
BACKUP SLIDES



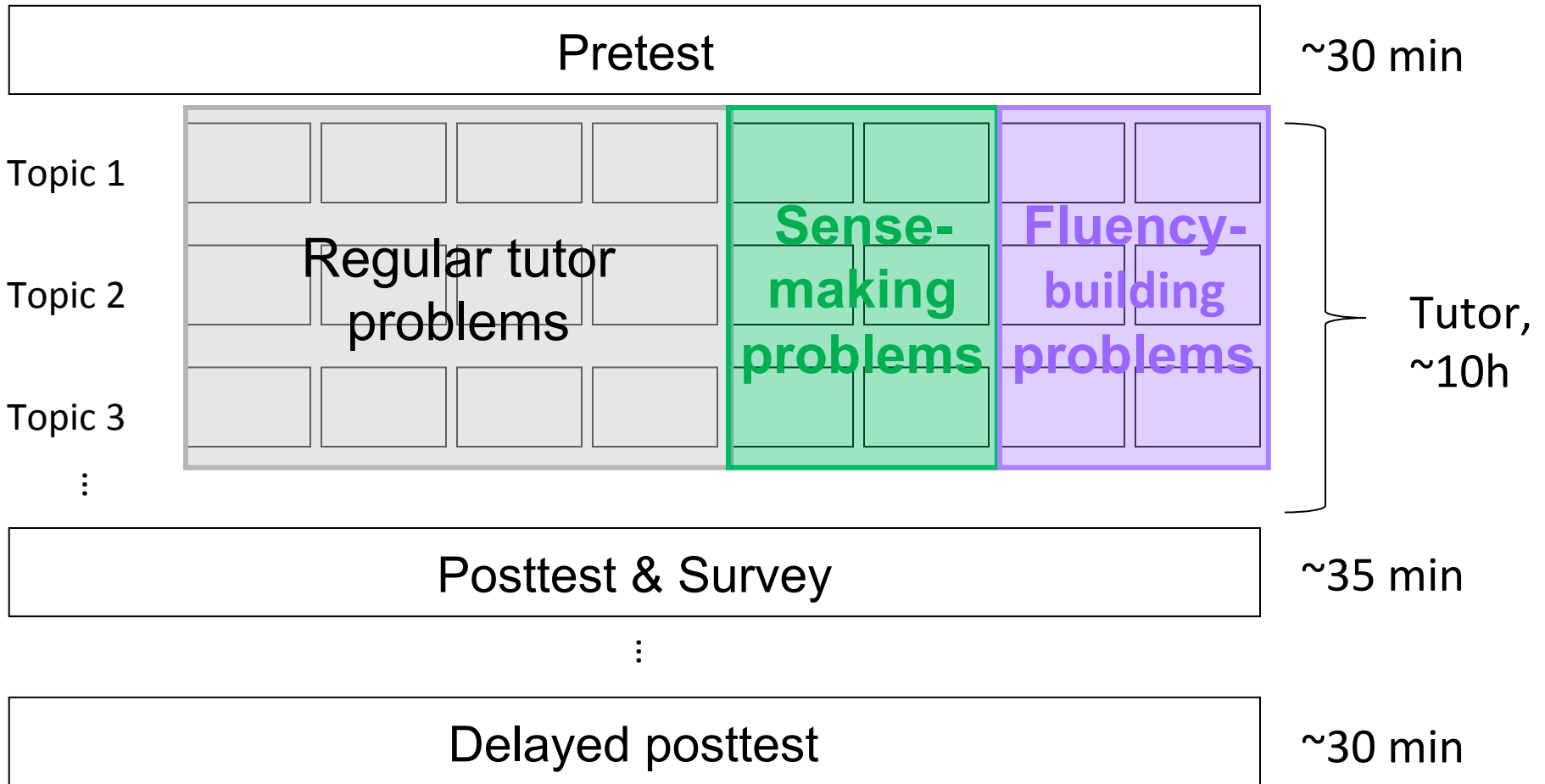
Sense-only condition



Fluency-only condition



Sense + fluency condition



Fluency-only vs. sense + fluency

Fluency-
only

Topic 1

--	--	--	--

Topic 2

--	--	--	--

Topic 3

--	--	--	--

⋮

Fluency-
building
problems

Sense +
fluency

Topic 1

--	--	--	--

Topic 2

--	--	--	--

Topic 3

--	--	--	--

⋮

Sense-
making
problems

Fluency-
building
problems



Sense-only vs. sense + fluency

Sense-only

Topic 1

--	--	--	--

Topic 2

--	--	--	--

Topic 3

--	--	--	--

⋮

Sense-making problems

Sense + fluency

Topic 1

--	--	--	--

Topic 2

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Topic 3

--	--	--	--

⋮

Sense-making problems

Fluency-building problems

