How we learn versus how we think we learn: Implications for the design and evaluation of instruction

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The problem:

- Conditions of instruction that make performance improve rapidly often fail to support long-term retention and transfer,

  …*whereas*

- Conditions of instruction that appear to create difficulties for the learner, slowing the rate of *apparent* learning, often optimize long-term retention and transfer

Learning versus *performance*

- Empirical evidence:
  - Old evidence: Learning without performance:
    - “Latent learning” studies;
    - Motor skills studies
  - Newer evidence: Performance with little or no learning;
  - The bottom line:
    - What we can observe is performance;
    - What we must infer is learning;
    - …and the former is an unreliable guide to the latter.

Corresponding conceptual distinctions:

- Hull (1943):
  - *Momentary reaction potential versus*
  - *Habit strength*
- Estes (1955):
  - *Response strength versus*
  - *Habit strength*
- Bjork & Bjork (1992):
  - *Retrieval strength* versus
  - *Storage strength*

The tendency to, and perils of, interpreting *retrieval strength* as *storage strength*

- Retrieval strength is heavily influenced by recency and cues that are available now, but are unlikely be available later

- Interpreting retrieval strength as storage strength (i.e., *learning*) contributes greatly to our (and our teachers) over-estimating the degree to which learning has been achieved.

Examples of manipulations that introduce "desirable difficulties" (Bjork, 1994) for the learner

- Varying the conditions of learning
- Distributing or spacing study or practice sessions
- Using tests (rather than presentations) as learning events
- Providing "contextual interference" during learning (e.g., *interleaving* rather than *blocking* practice)

The word *desirable* is important …

- Many difficulties are *undesirable* during learning, after learning, and forever after
- Desirable difficulties are desirable because responding to them (successfully) engages processes that support learning, comprehension, and remembering
  - They become undesirable difficulties if the learner is not equipped to respond to them successfully.
  - Generation effects as an example.

June 2009 message from Tim (“Oz”) Ozman

(Chief, Ground Maintenance Branch; CASCOM Training Directorate; Fort Lee, Virginia)

- “To provide an example of how I think I'm trying to achieve transfer --currently we teach a mechanic to trace an electrical schematic of a particular vehicle, practice on that vehicle, then test on that vehicle. My approach would be to train on the most complex schematic they will encounter, practice on totally different pieces of equipment, followed by testing on yet another item of equipment. The intent is to train them to interpret schematics, not just one specific schematic. My understanding from your writing is that performance on the test may suffer (near in time), but will increase remote in time (say, 6 months after graduating the course). Am I on the right track?”

Varying the conditions of learning (Example: Kerr & Booth, 1978)

Design

- Two age groups: 8-year-olds & 12-year-olds
- Task: beanbag toss to target on floor (occluded)
- Conditions of Practice:
  - Fixed: All practice at a fixed (criterion) distance;
  - Varied: Practice at criterion distance +/- one foot (never at the criterion distance)

Kerr and Booth (1978): Results

- Absolute Error (inches) on Final Test (3-feet distance for 8-year-olds)

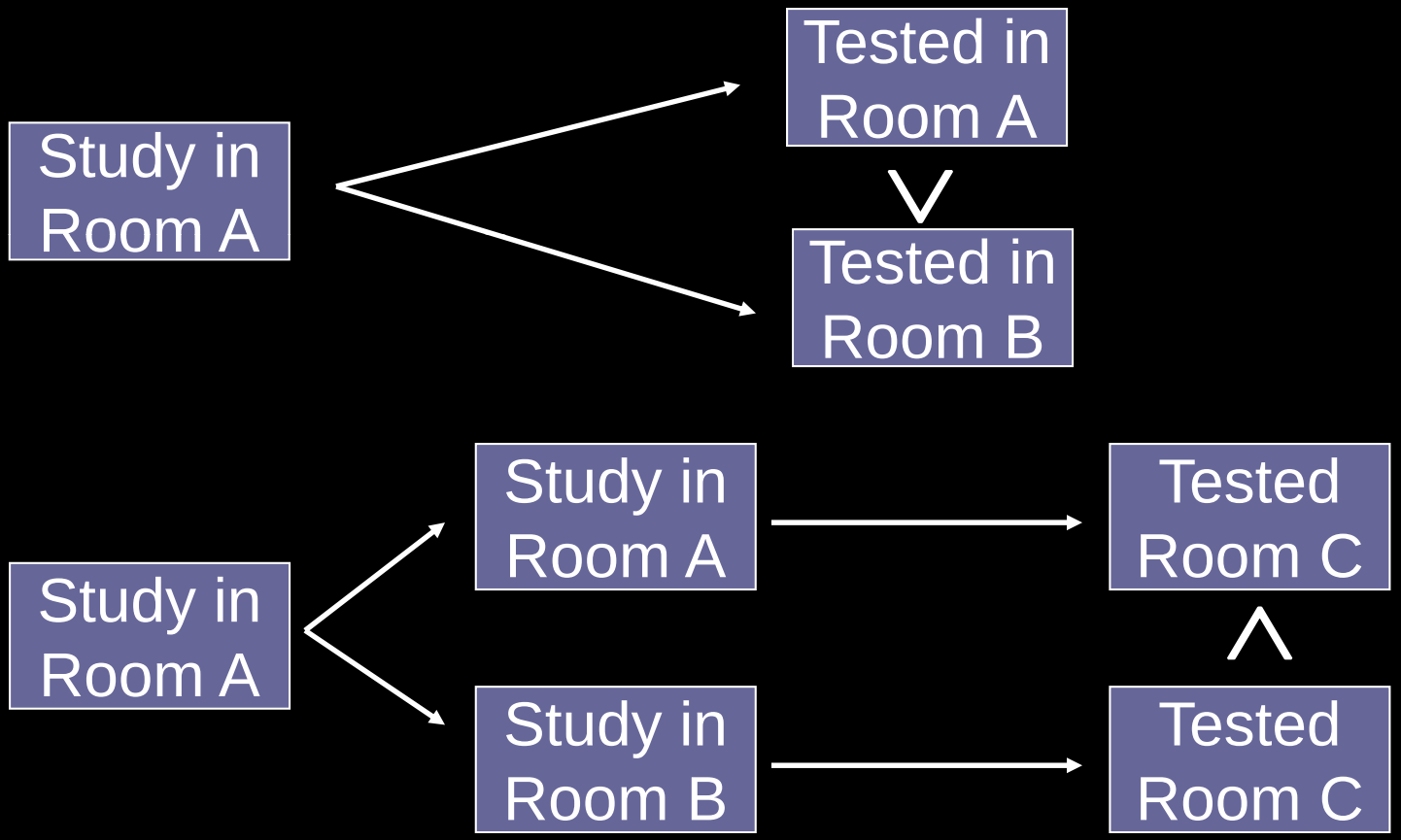
	Age of Participant	
Practice Condition	8 years	12 years
Fixed (criterion)	8.31	5.55
Varied (criterion +/- 1 ft)		

Kerr and Booth (1978): Results

- Absolute Error (inches) on Final Test (3-feet distance for 8-year-olds)

	Age of Participant	
Practice Condition	8 years	12 years
Fixed (criterion)	8.31	5.55
Varied (criterion +/- 1 ft)	5.42	4.63

Varying the environmental context of learning (Smith, Glenberg, & Bjork, 1978)



Distributing/Spacing of Practice

Baddeley & Longman (1979)

	Training Schedule		
1 x 1 hr	2 x 1 hr	1 x 2 hr	2 x 2 hr

Hours to Learn Keyboard			
34.9	42.6	43.2	49.7

Mean Satisfaction Rating *1 (Very Satisfactory) to 5 (Very Unsatisfactory)*			
2.40	1.86	2.00	1.73

Tests versus presentations as learning events

- Testing as pedagogy versus testing as assessment
  - Retrieving information or procedures is a learning event
    - The information/procedures recalled become more recallable in the future than they would have been otherwise;
    - It is substantially more powerful event than is being presented the information (inflatable life vest example)
  - Tests provide far better feedback as to what has or has not been learned/understood (vs. presentations)
  - Tests potentiates the effectiveness of subsequent study
- Survey of illustrative findings

The power of tests as learning events: Roediger and Karpicke (2006)

- To-be-learned text passage on the sun or on sea otters (about 30 idea units per passage)

- Three conditions
  - SSSS: four consecutive 5-min study periods
  - SSST: three study period plus a test of recall for the passage
  - STTT: one study period plus four consecutive tests of recall for the passage

Roediger & Karpicke (2004)
(Passage on the sun or on sea otters; about 30 idea units in each passage)

Table 3

Mean number of times subjects were able to read the entire passage during 5-minute study periods in Experiment 2

	Study Period				
Condition	1	2	3	4	Sum
SSSS	3.4	3.5	3.6	3.7	14.2
SSST	3.2	3.5	3.6		10.3
STTT	3.4				3.4

Roediger & Karpicke (2004)

Table 5

Mean proportion of idea units recalled on the retention tests and forgetting scores in Experiment 2

	Retention Interval		
Condition	5 min	1 week	Forgetting
SSSS	.83		
SSST	.78		
STTT	.71		

Roediger & Karpicke (2004)

Table 5

Mean proportion of idea units recalled on the retention tests and forgetting scores in Experiment 2

	Retention Interval		
Condition	5 min	1 week	Forgetting
SSSS	.83	.40	
SSST	.78	.56	
STTT	.71	.61	

Roediger & Karpicke (2004)

Table 5

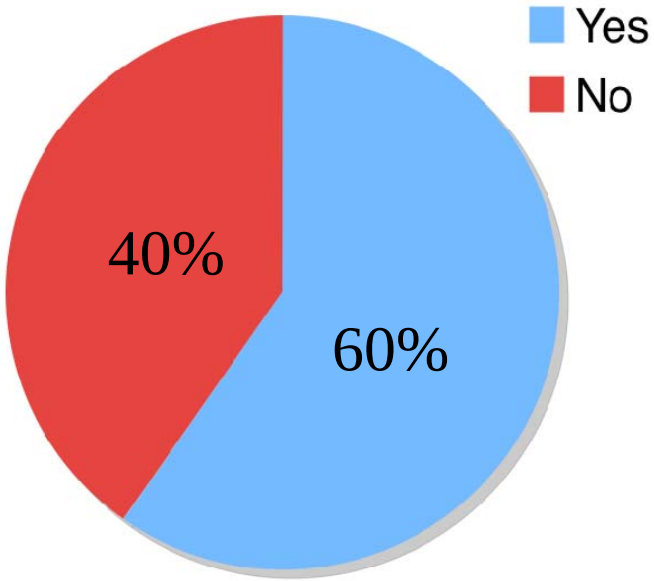
Mean proportion of idea units recalled on the retention tests and forgetting scores in Experiment 2

	Retention Interval		
Condition	5 min	1 week	Forgetting
SSSS	.83	.40	.43
SSST	.78	.56	.22
STTT	.71	.61	.10

Using tests to self-regulate one's learning: Kornell & Bjork (2008)

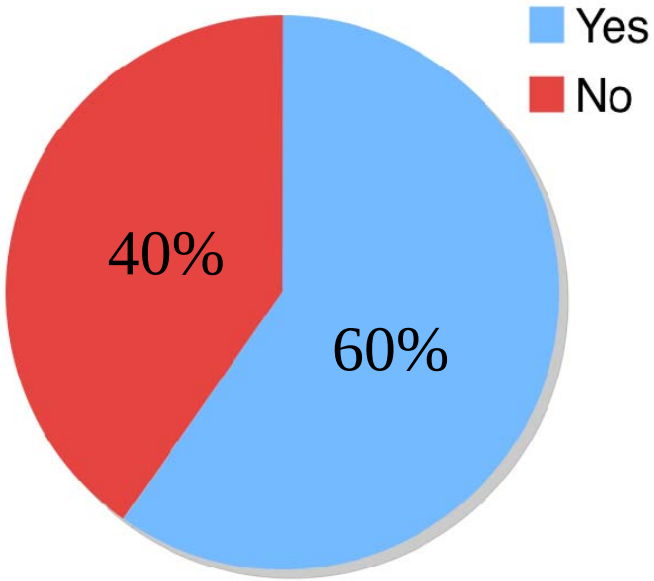
- Using flashcards is a very common study technique—and one that, potentially, taps into both the memory and metamemory virtues of testing;
- Dropping flashcards deemed to have been learned is common and, intuitively, a way to maximize the efficiency of study;
- But is dropping a good thing?

Real life flashcard habits

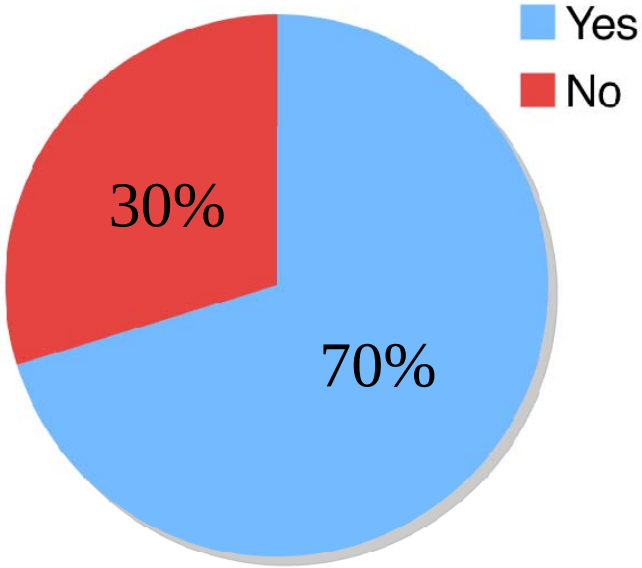


Do you study with flashcards in real life?

Real life flashcard habits



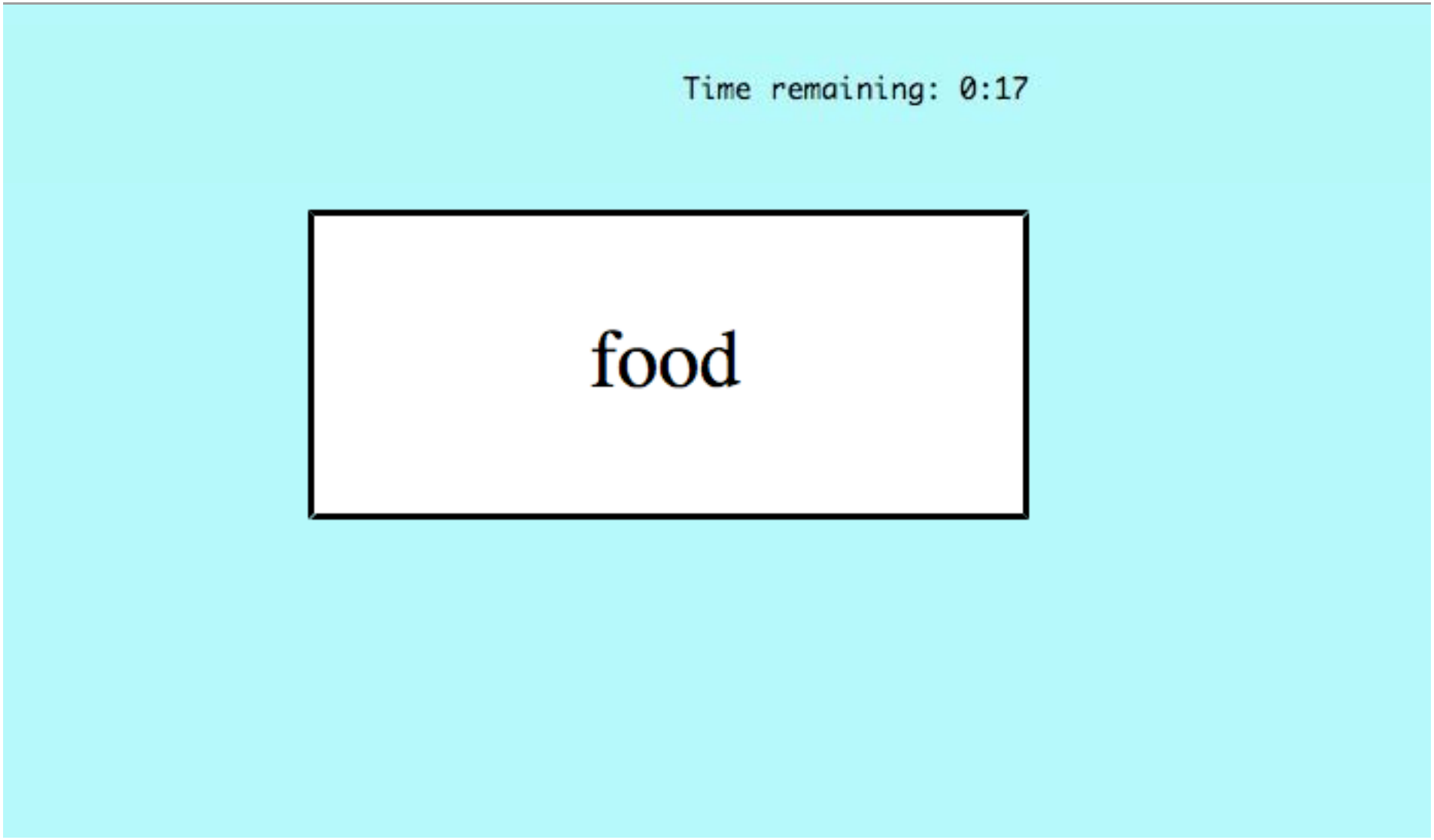
Do you study with flashcards in real life?



If so, do you remove cards from your stack as you go?

Method: Kornell & Bjork (2008)

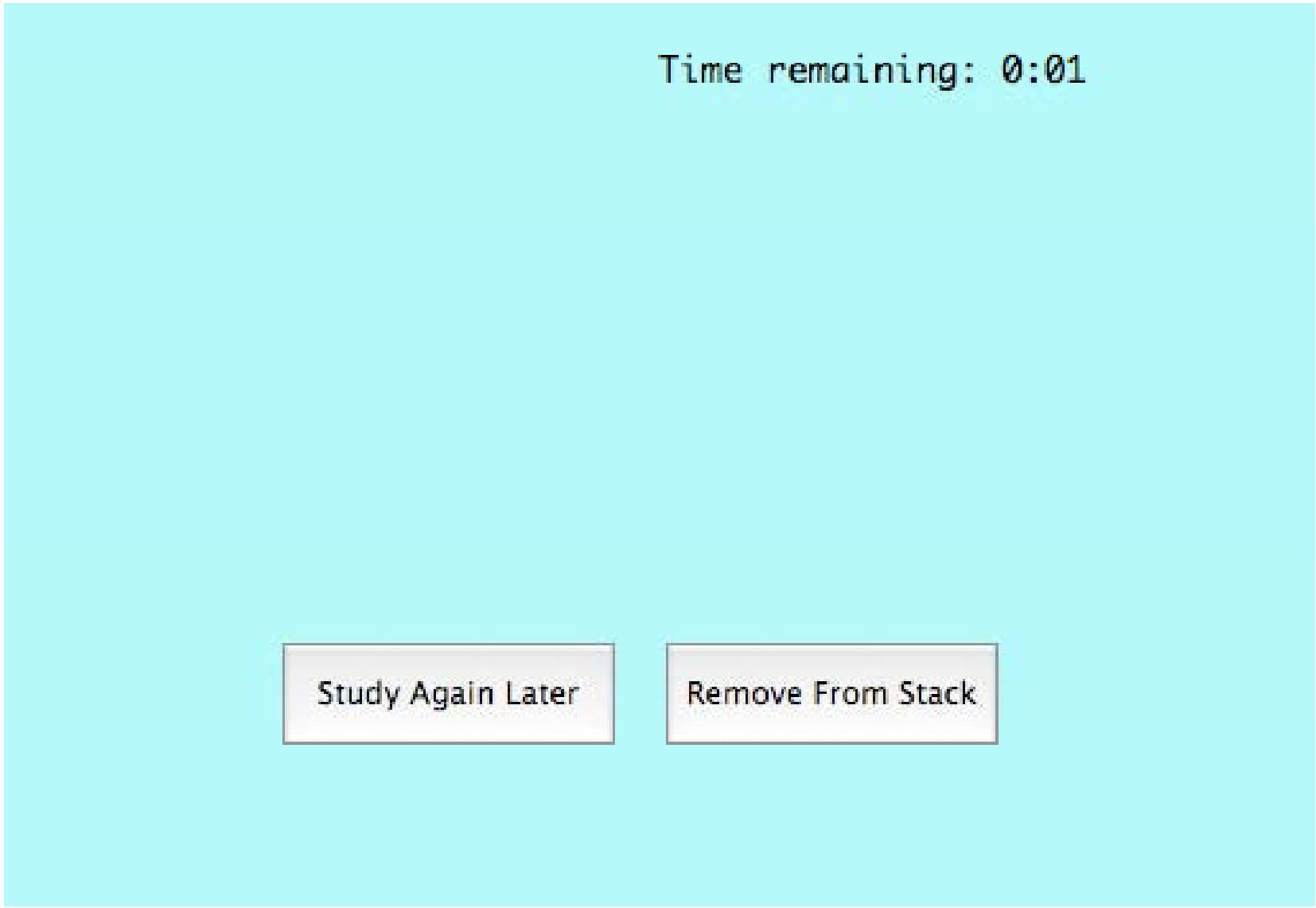
- Participants learned two lists of 20 English-Swahili word pairs via a computerized flashcard procedure
- Self-regulation conditions
  - Dropping items permitted for one list;
  - Not for the other list (order counterbalanced)
  - (Important: Total study time fixed at 10 min per list)
- Delay before the final test
  - Immediate
  - 1 week


Time remaining: 0:17
food

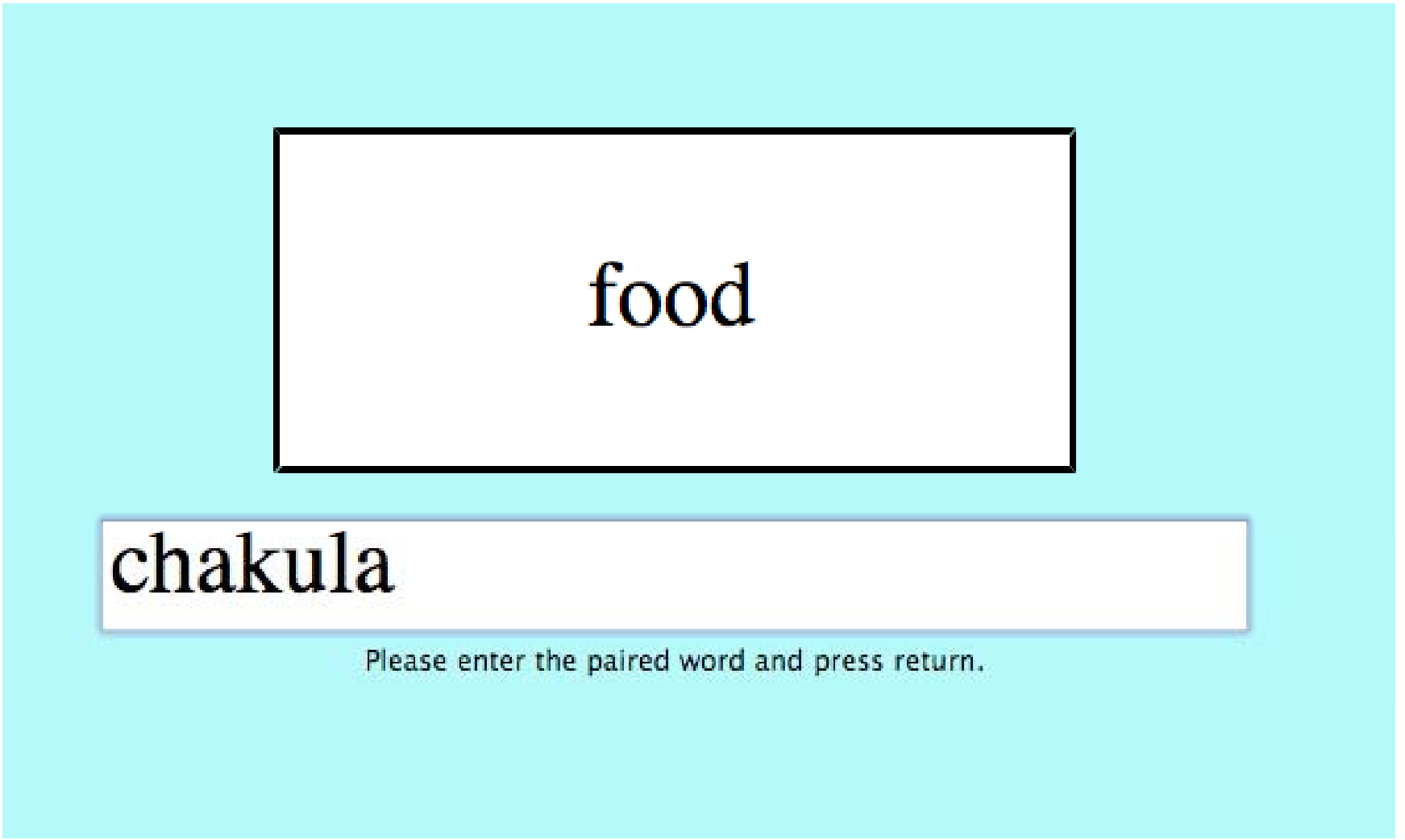
Time remaining: 0:16

chakula

No-drop condition

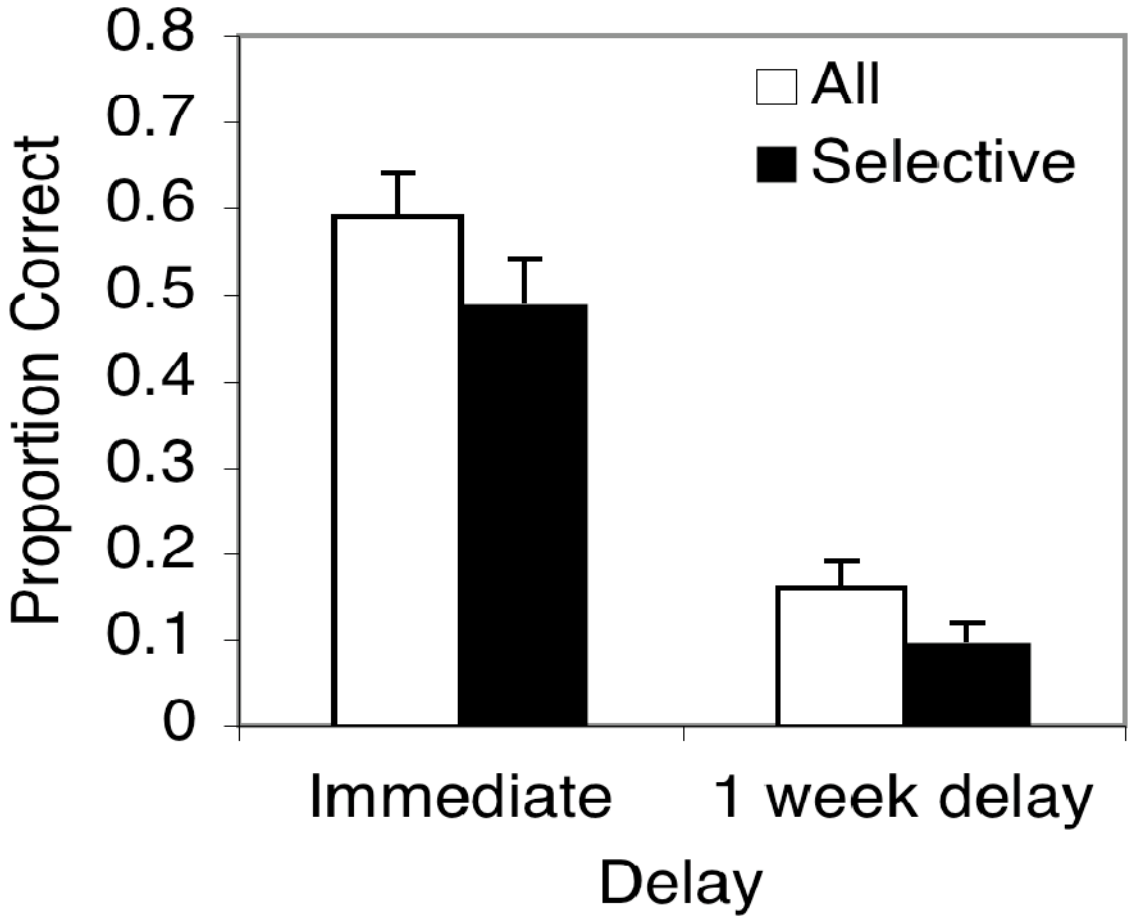


Drop condition



Final test (with answer filled in)

Results



Statistics: All > Selective, No interaction

Why did being permitted to drop items actually impair learning?

- Possible factors
  - Spacing of trials on a given pair decreases as items are dropped;
  - Participants' metacognitive judgments are flawed
    - Dropping, to be effective, requires accurate judgments of learning;
    - Subsequent experiments revealed that participants dropped items that would have profited greatly from even a single additional trial
- Remaining question:
  - When items are dropped, is the cost to their later recall attributable to their not being studied again, not being tested again, or both?
  - Karpicke and Roediger's (2008) study

The study/test method for learning vocabulary items and other materials

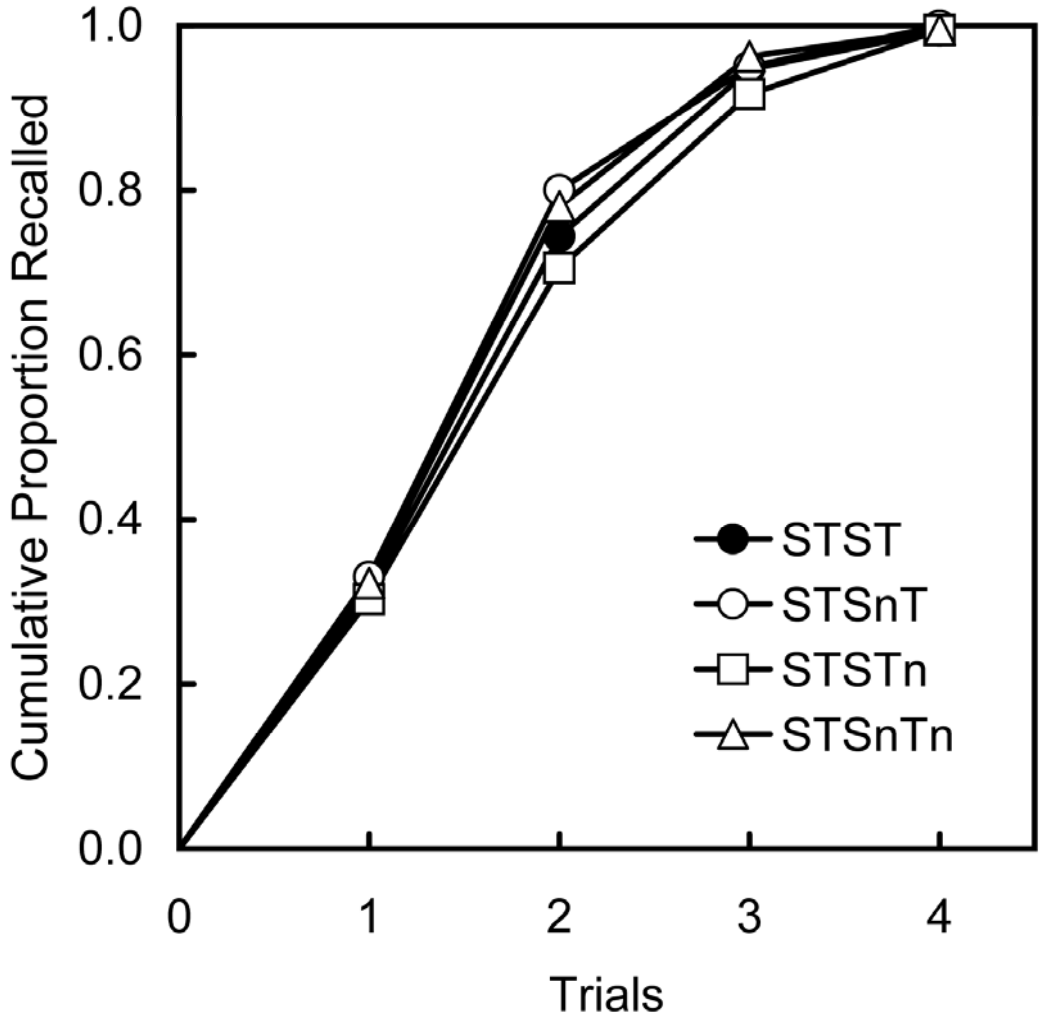
- Alternating study and test cycles (through to-be-learned list of items)
  - Study cycle: (…, *Lesa*: scarf, …)
  - Test cycle: (…, *Lesa*: __?__, …)
  - Study cycle: (…, *Lesa*: scarf, …)
  - Test cycle: (…, *Lesa*: __?__, …)
  - …
- Standard assumption: Study cycles provide opportunities for learning; test cycles assess learning

Kapicke and Roediger (*Science*, 2008)

- Vocabulary learning
  - 40 Swahili-English pairs
  - Four Study/test cycles:
    - Study cycle: … *mashua:* boat, *lesa:* scarf, …
    - *Test cycle: … lesa:* scarf, *mashua:* boat, …
- Conditions
  - STST: Study all, test all (standard)
  - ST ST_N: Study all, test non-recalled
  - ST S_NT: Study nonrecalled, test all
  - ST S_NT_N: Study nonrecalled, test nonrecalled

LEARNING PHASE

(Karpicke & Roediger, 2008)



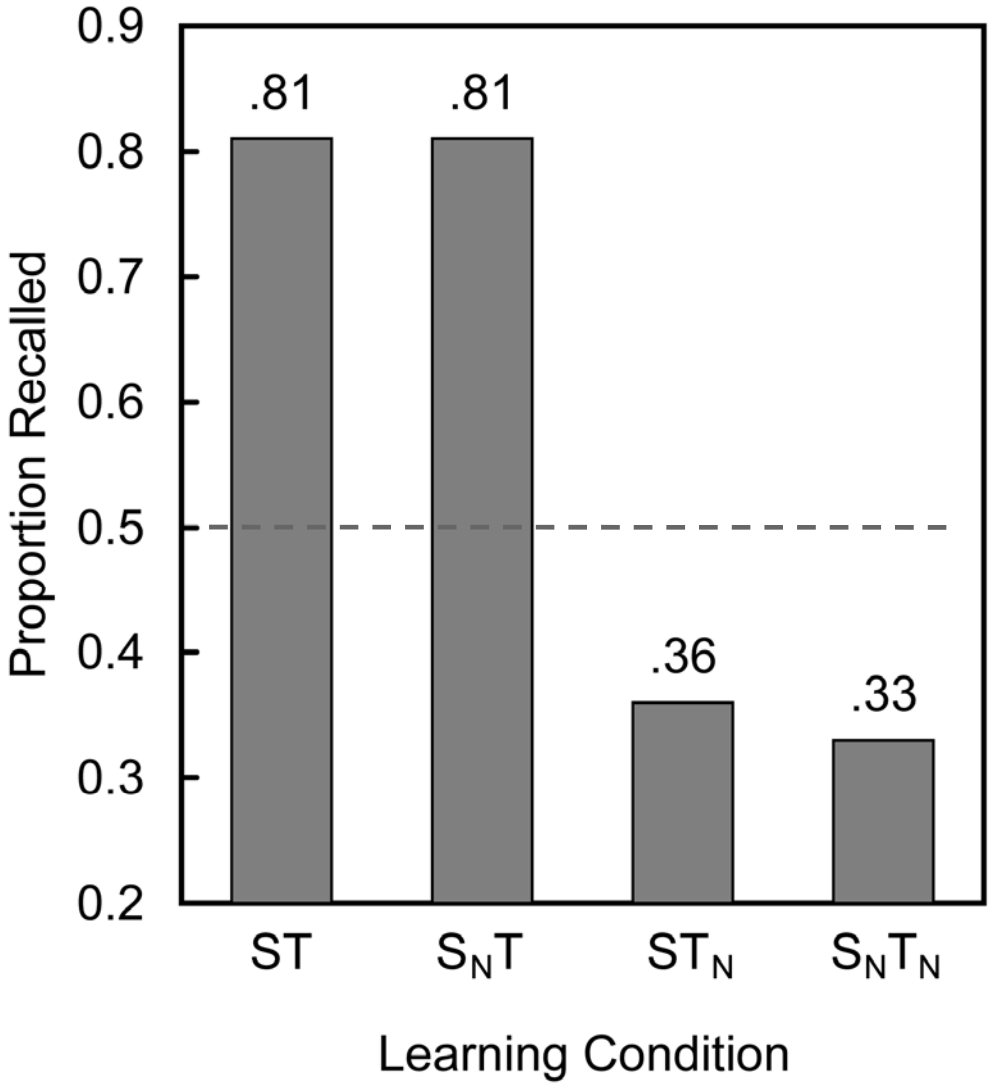
STUDENT PREDICTIONS AT THE END OF FOUR STUDY/TEST CYCLES

"How many words will you recall in 1 week?"

All conditions = ~ 50%

(no significant differences)

ONE WEEK LATER



Repeated studying after learning had no effect on delayed recall, but repeated testing produced a large positive effect.

Do failed tests potentiate subsequent learning? (Kornell, Hays, & Bjork, 2009)

- Prior experiments comparing pretest + study with no-pretest + study have suffered from selection effects
  - Correct answers on the pretest select out easier-than-average items;
  - Wrong answers on the pretest select out harder-than-average items.
- Solution: Use questions that are impossible, or essentially impossible, to answer correctly

Fictional Questions

What is the last name of the person who ran away from the Giants?	Andrew
What is the last name of the person who panicked America with his book 'Plague of Fear'?	Hayden
What is the last name of the infamous traitor in the Twelve Years War?	Landon
What peace treaty ended the Calumet War?	Harris
Which comic book character constantly refers to himself as 'The Mighty Green One'?	Swampman
What was designed to defeat the Creton and now refers to a weapon?	iron-whip
What kind of bird spoke to Amelia in the story 'Over the Rainbow'?	Cockatoo
What is the crown called which is worn as a symbol of regal or imperial power?	wreath
What is a community of green beetles called?	village
What is the name of the sailor who took the first solo voyage around Cape Evergreen?	Hutchinson

Real Questions

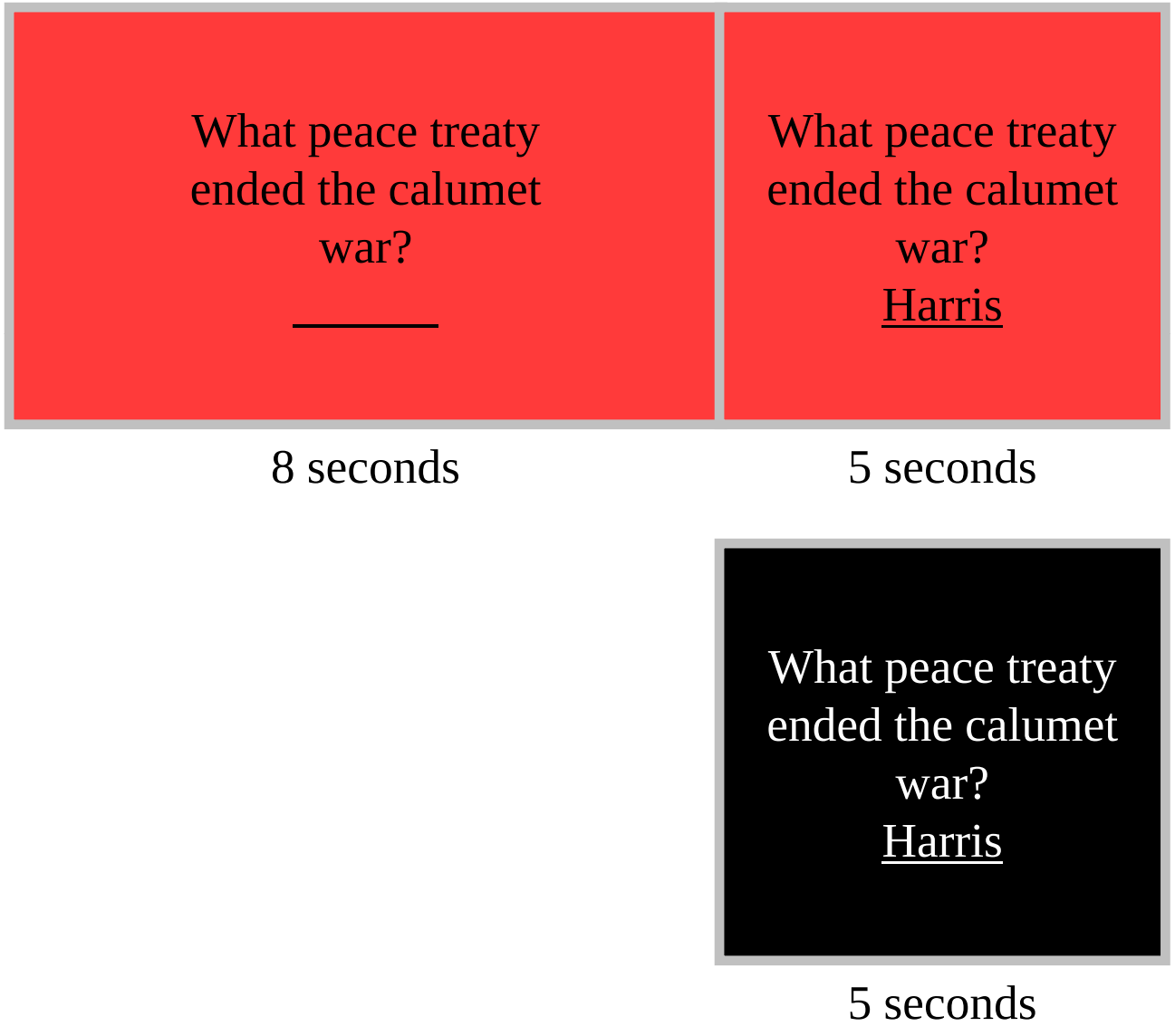
What is the term for someone who doubts but does not deny the existence of God?	agnostic
What is the term for sexual pleasure derived from being subjected to pain?	masochism
What was the name of the disorder depicted by Dustin Hoffman's character in the movie 'Rain Man'?	autism
What is the name of King Arthur's sword?	Excalibur
What is the first name of the school teacher who was chased by the headless horseman in 'The Legend of Sleepy Hollow'?	Ichabod
What is the name of the short sword fastened to the end of a musket or rifle?	bayonet
What is the last name of the author of 'The Hobbit'?	Tolkien
What is the fin on the back of a fish called?	dorsal
What is the name of the three leaf clover which is the emblem of Ireland?	shamrock
What are people who explore caves called?	spelunkers

Method overview

- 40 trivia questions
  - Test + study condition
    - 10 real, 10 fictional
  - Pure study condition
    - 10 real, 10 fictional
- Final test on all 40 questions

Experiment 1 (n=25)

Is an unsuccessful test better than nothing?



Instructions

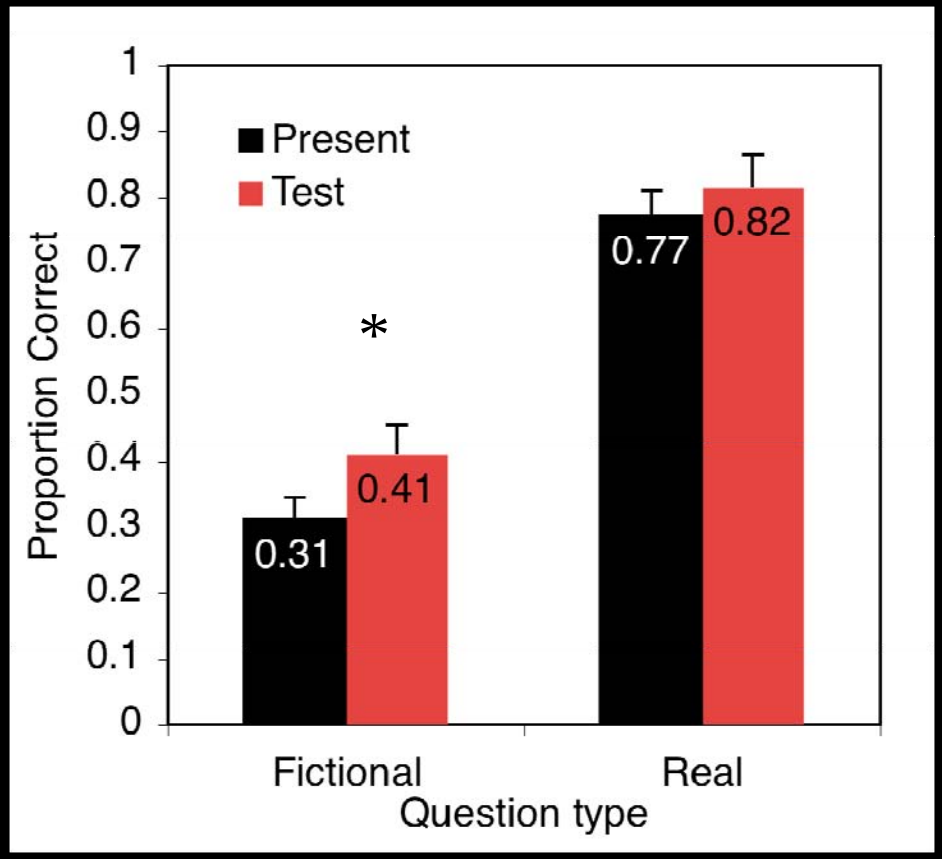
WELCOME
In this experiment you're going to learn the answers to general information questions.

First you'll do a study phase. There will be two types of trials during the study phase: On some trials you will be asked a question, and then shown the answer. Try to think of the answer (and type it in) before it is shown. On other trials the question and answer will be presented together.

After the study phase ends, there will be a test phase. During the test phase you will be asked to answer all of the questions you studied during the study phase (i.e., every question, regardless of how you studied it).

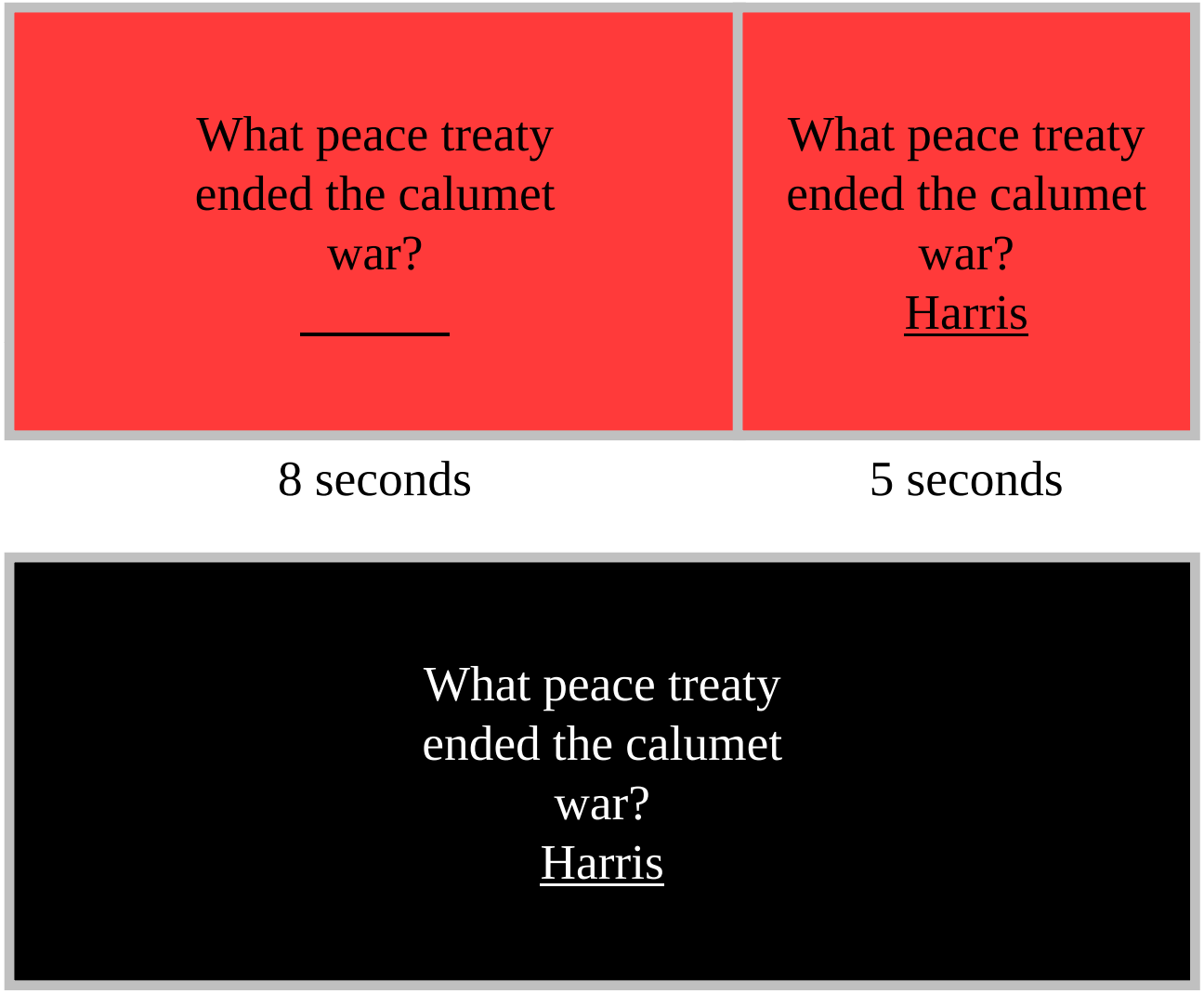
Keep in mind that, during the study phase, your goal is to learn as many answers as you can.

Results: Experiment 1

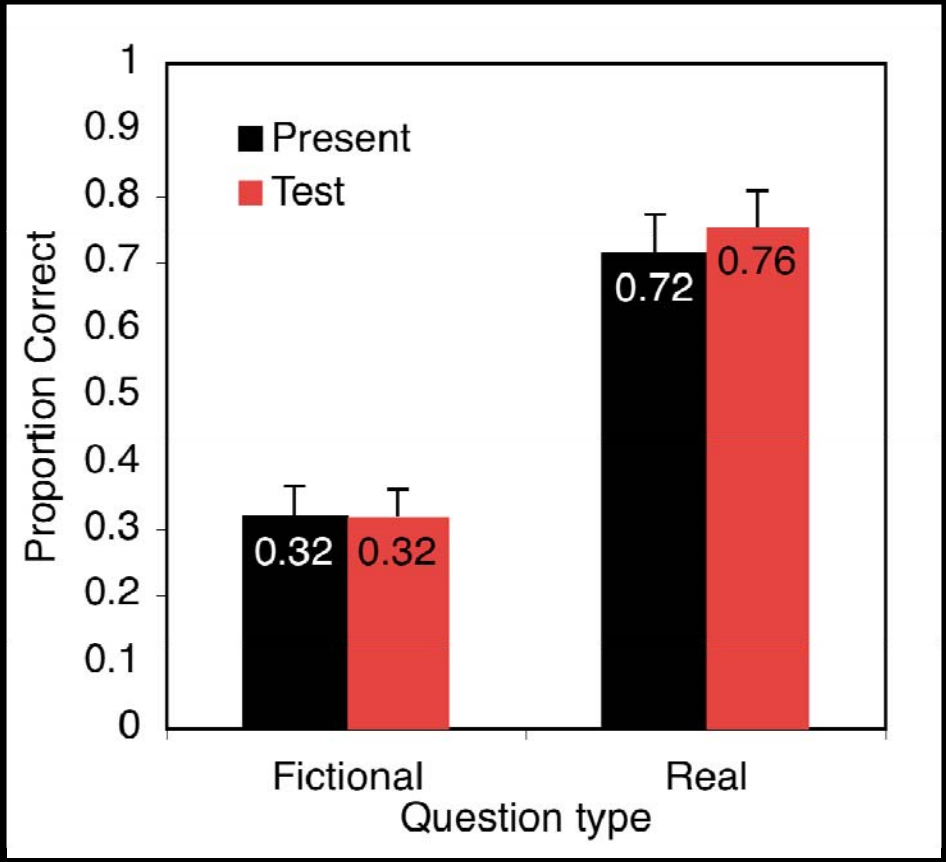


Experiment 2 (n=20)

Is an unsuccessful test better than a presentation?



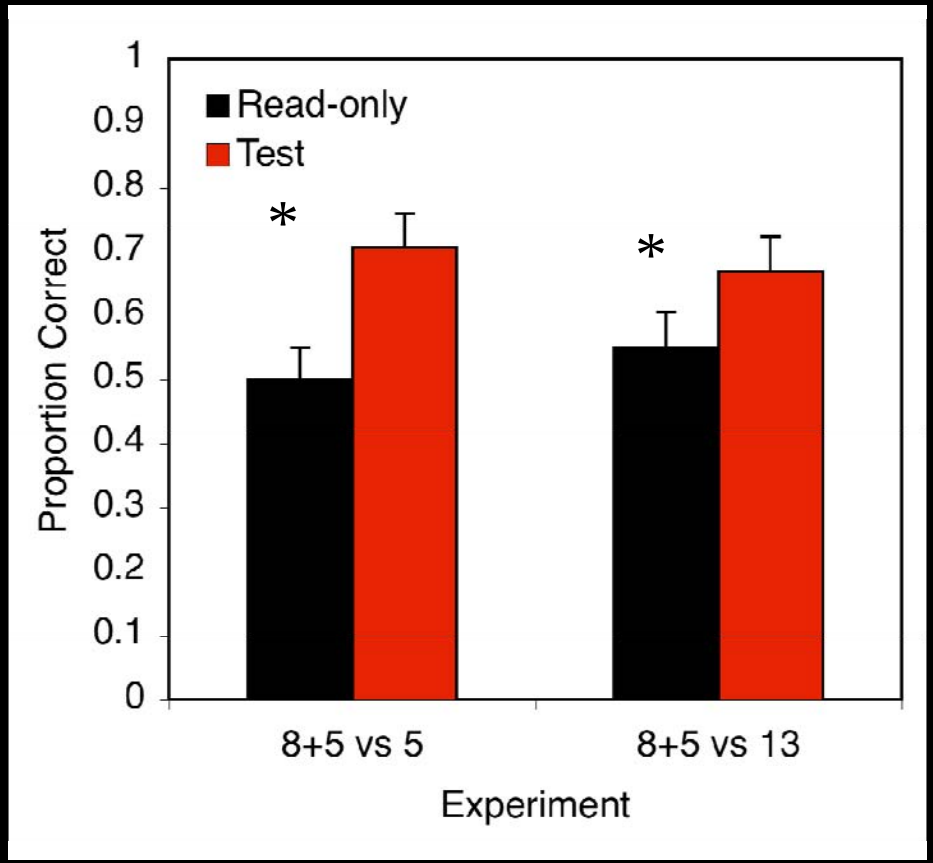
Results: Experiment 2



Experiments 3 and 4: verbal materials

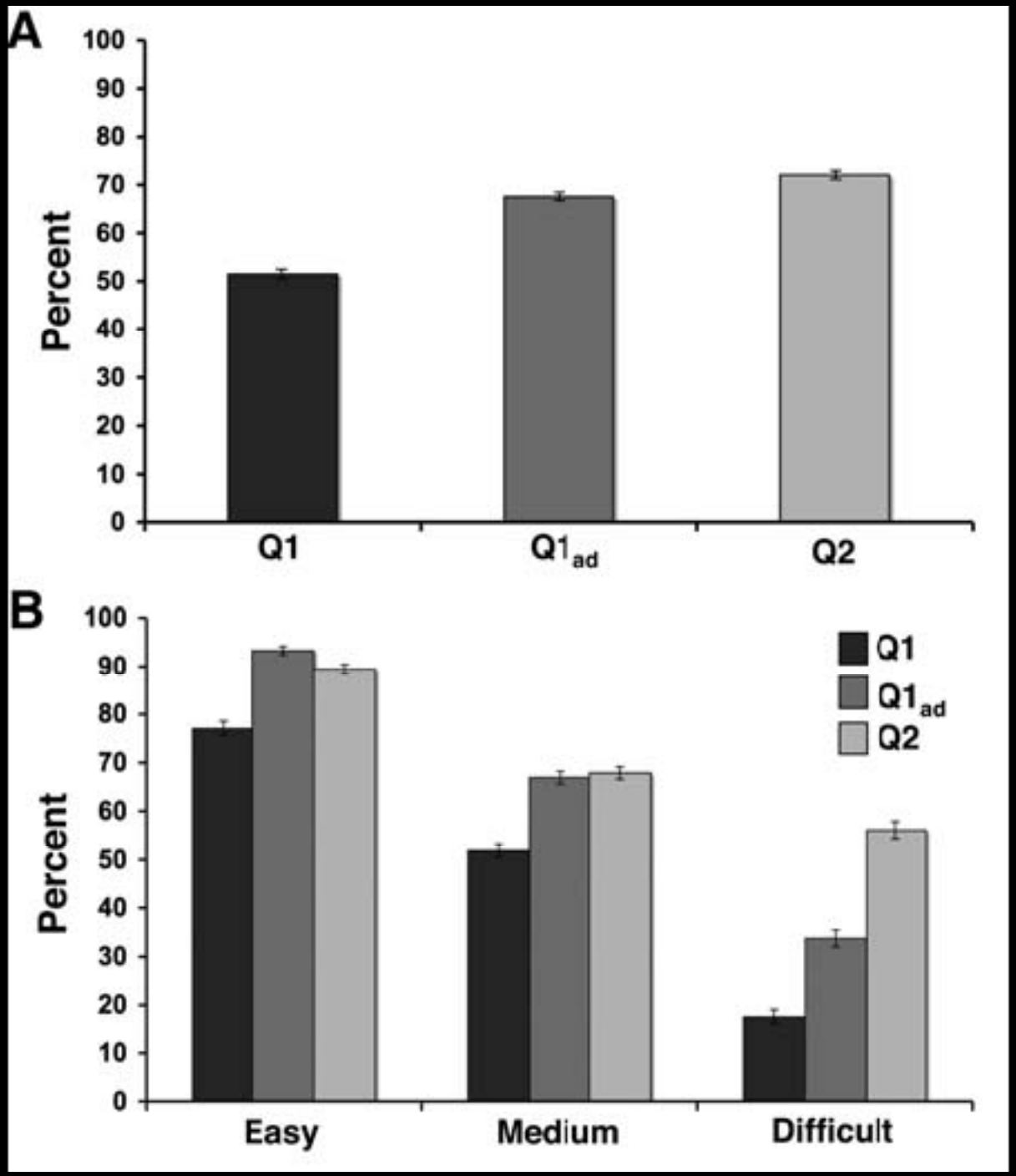
- Low associates
  - Whale-???
  - Whale-Mammal
- Pairs chosen (from norms) so that
  - < 5% of responses are the to-be-learned associate;
  - Those trials eliminated from the analysis
- Designs: 8 sec (test) + 5 sec (study)
  - 5 sec study (Experiment 3)
  - 13 sec study (Experiment 4)

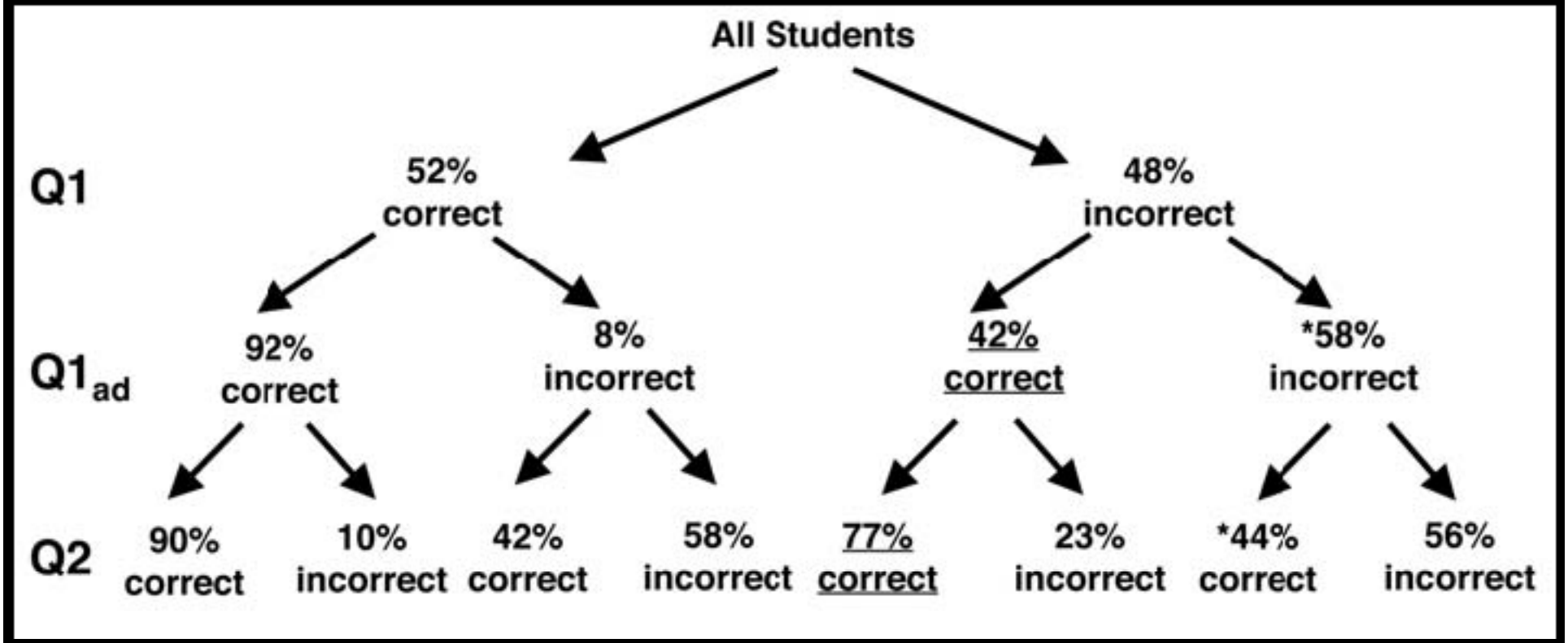
Results: experiments 3 and 4



Using clickers to tap the benefits of testing: Smith, Wood, Adams, Wieman, Knight, Guild, and Su (*Science*, 2009)

- Undergraduate genetics course for biology majors, University of Colorado
- Procedure:
  - 1. Individuals answer multiple-choice question Q1;
  - 2. Distribution of answers displayed;
  - 3. Individuals discuss their answers with neighboring peers and revote on the question;
  - 4. Individuals answer a second question, Q2, which differs from Q1, but “required application of the same principles or concepts to solve“
- The issue


A
Percent
100
90
80
70
60
50
40
30
20
10
0
Q1
Q1ad
Q2
B
Percent
100
90
80
70
60
50
40
30
20
10
0
Q1
Q1ad
Q2
Easy
Medium
Difficult


All Students
Q1
52% correct
48% incorrect
Q1ad
92% correct
8% incorrect
42% correct
*58% incorrect
Q2
90% correct
10% incorrect
42% correct
58% incorrect
77% correct
23% incorrect
*44% correct
56% incorrect

Providing “contextual interference” during learning

- *Interleaving* rather than *blocking* practice
  - Shea and Morgan (1979)
  - Simon and Bjork (2001)
  - Rohrer and Taylor (2007)
  - Ste-Marie, Clark, Findlay, & Latimer (2004)
- Consistent versus inconsistent “advanced organizers” (Mannes and Kintsch, 1987)
- Optimizing Induction (Kornell and Bjork, 2008)

Blocked versus random practice (e.g., Shea & Morgan, 1979)

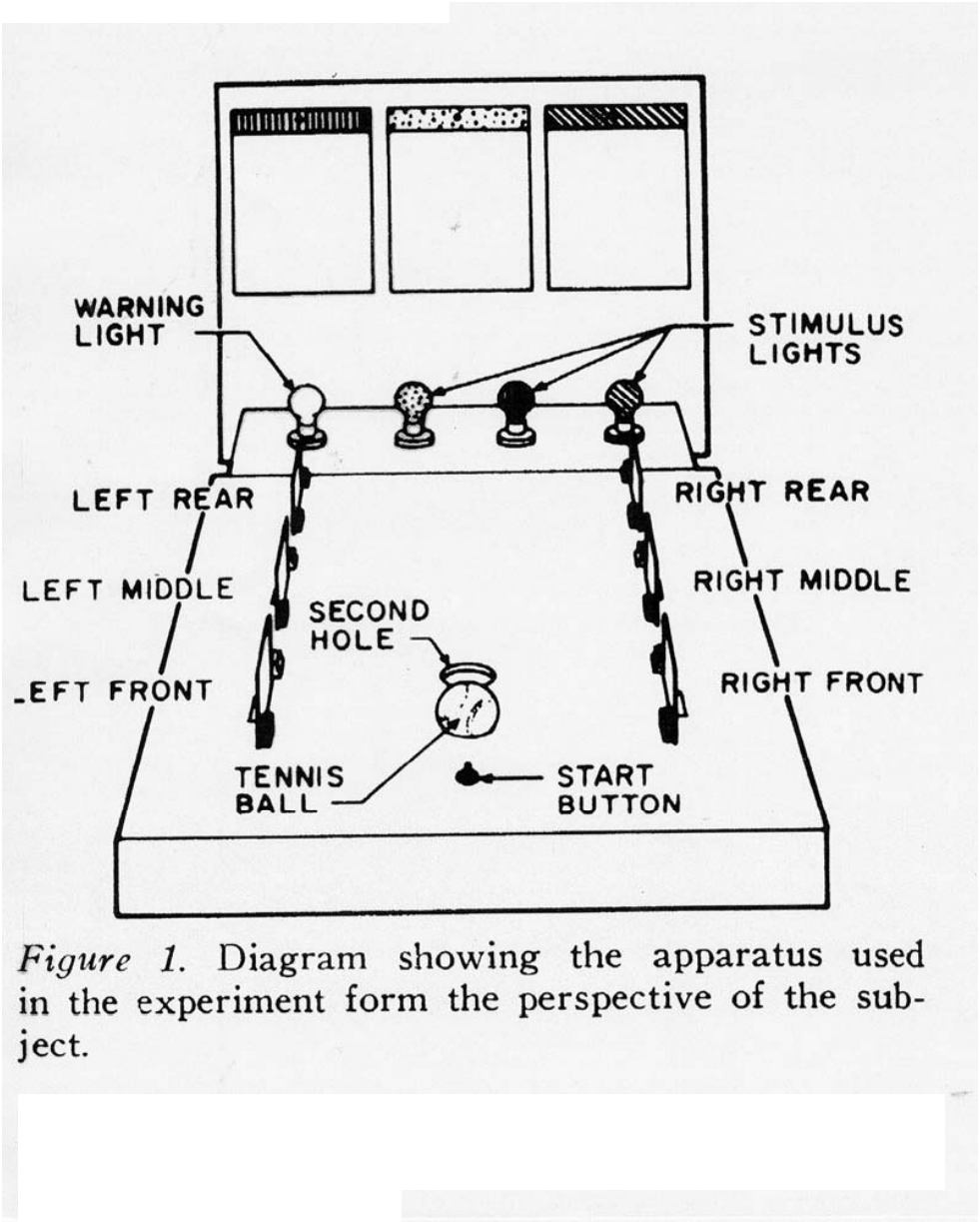


Figure 1. Diagram showing the apparatus used in the experiment form the perspective of the subject.

Shea & Morgan (1979): Results

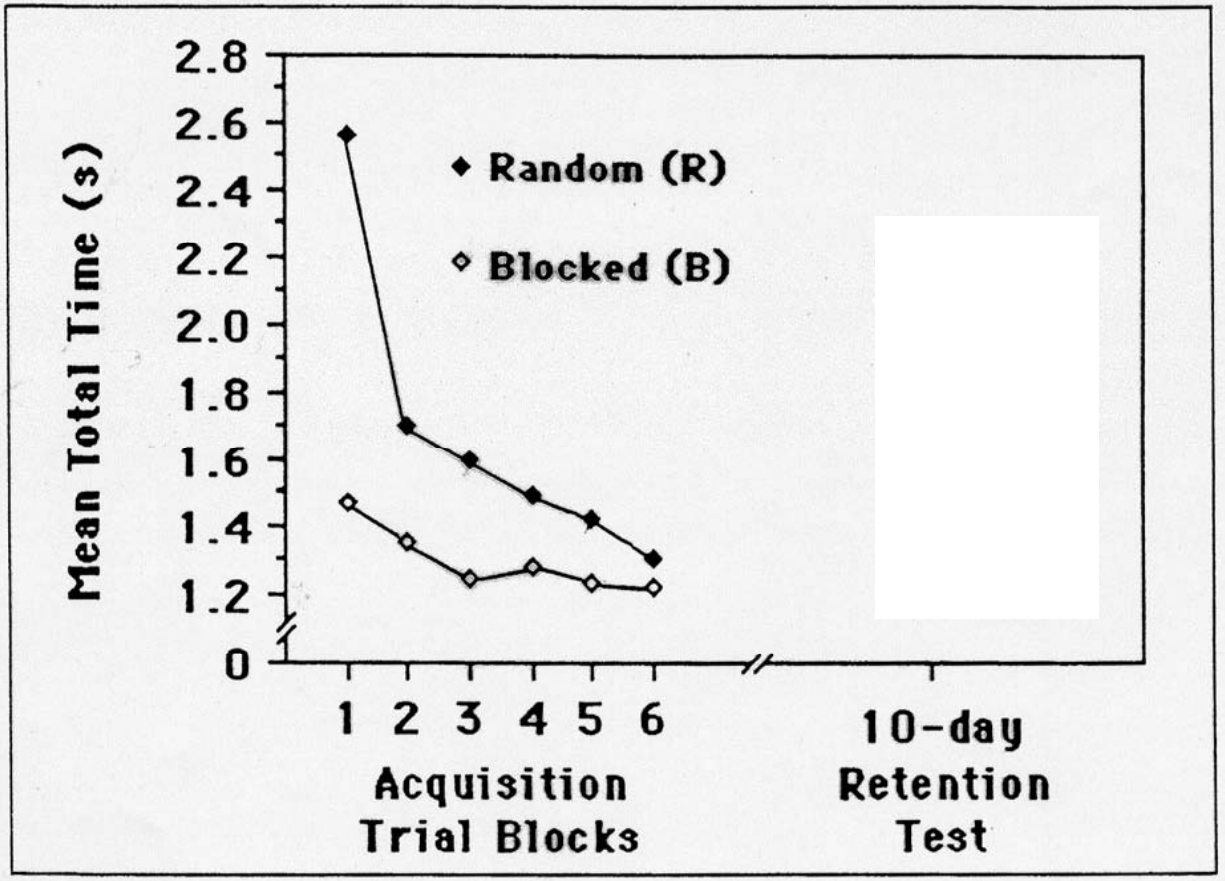
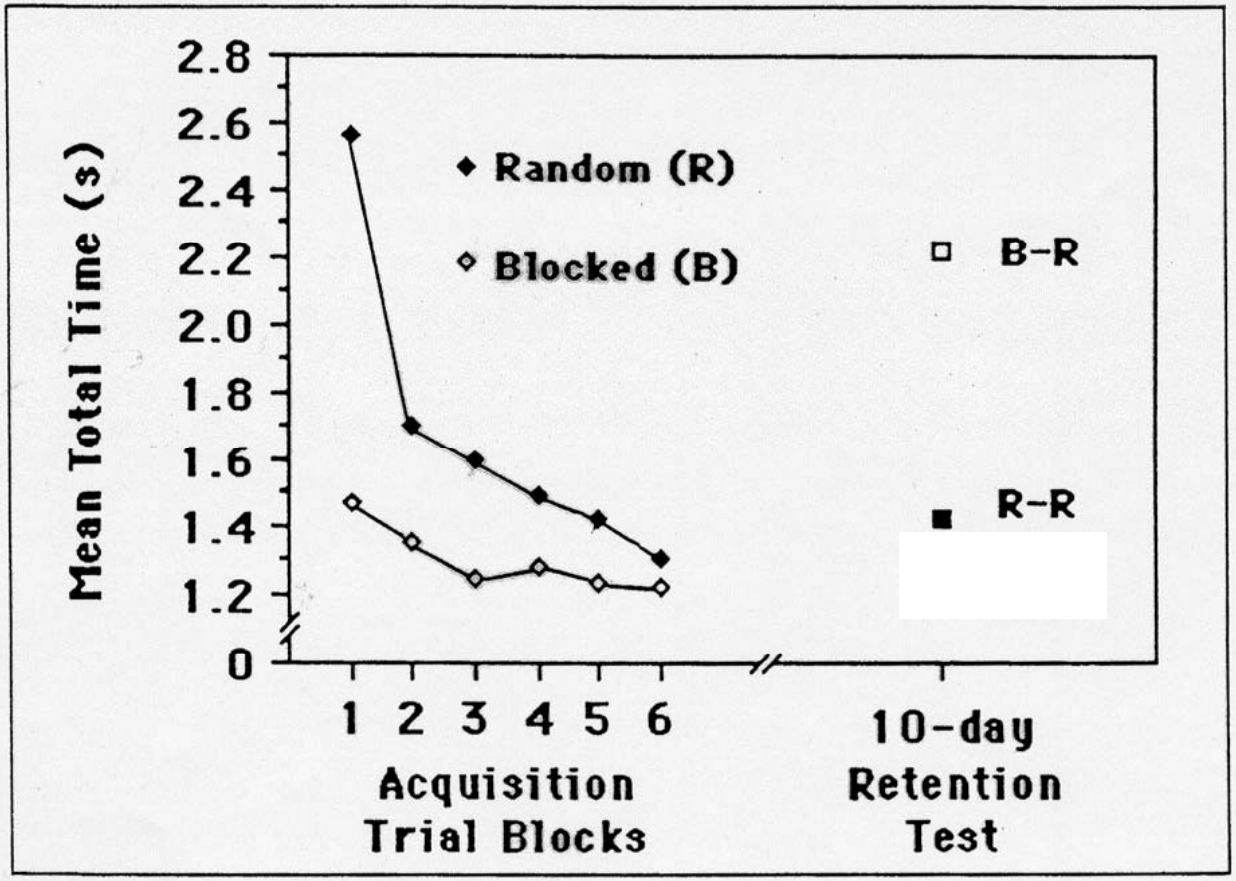


Fig. 1. Performance on movement speed tasks under random (R) and blocked (B) conditions in acquisition and, after 10 days, in retention tests under random or blocked conditions; in retention, the first letter indicates the acquisition condition, and the second represents the retention condition. Redrawn from Shea and Morgan (1979).



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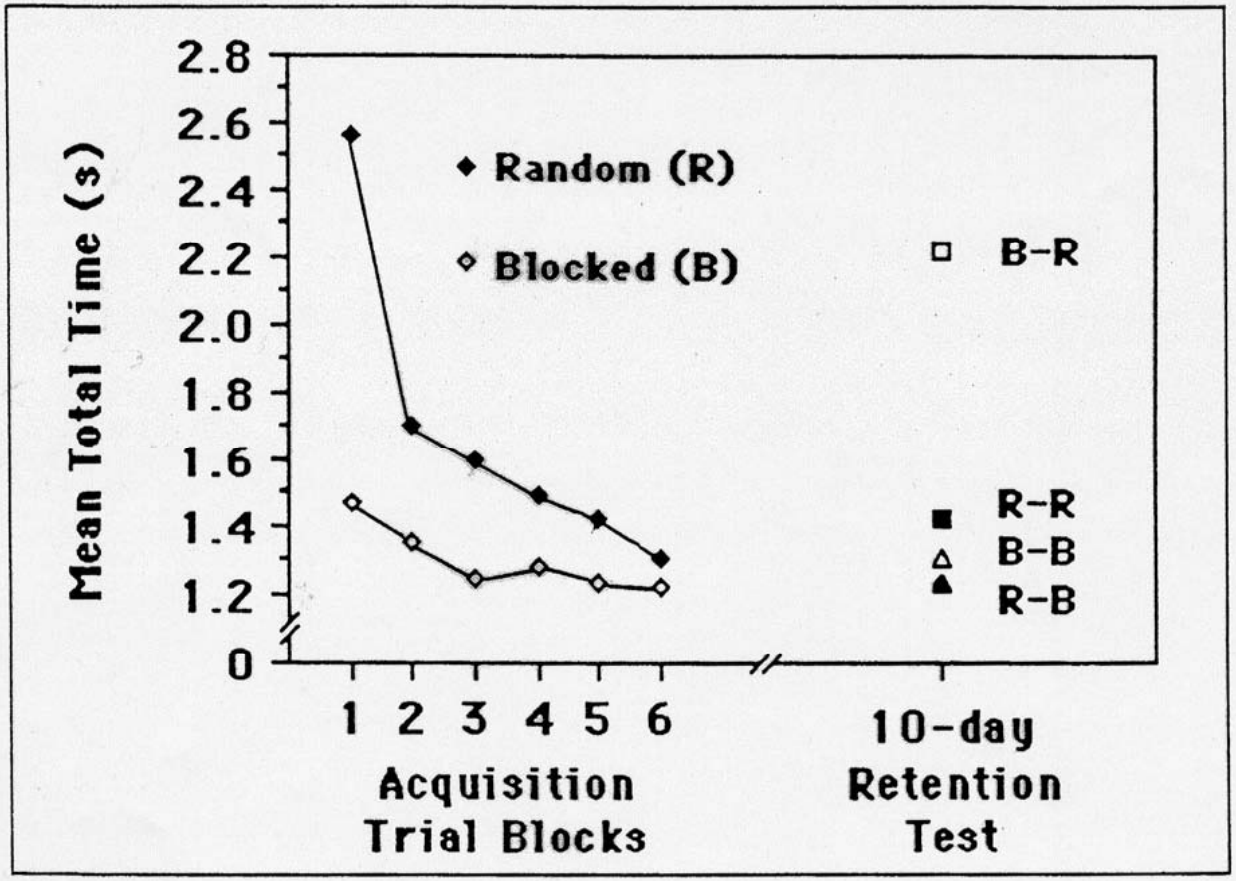

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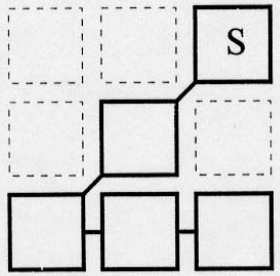
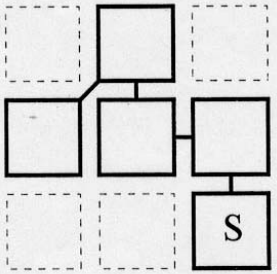
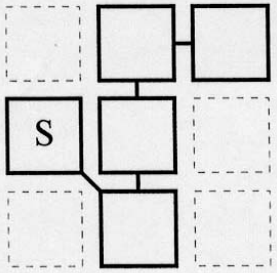
Simon & Bjork (2001)

To-Be-Learned Keystroke Sequences. Note: The key labeled "S" was the first in each sequence, and subjects had to follow the line to press the subsequent keys in the correct order.

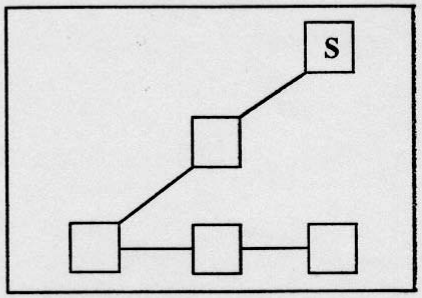
Keys	Color	Goal MT	Keyboard Pattern
9-5-1-2-3	Green	900 ms	
3-6-5-8-4	Red	1200 ms	
4-2-5-8-9	White	1500 ms	

Simon & Bjork (2001): A typical trial

4 seconds
(first 3 trials of each pattern)

Your goal movement time for the green pattern is 900 milliseconds.

3 seconds



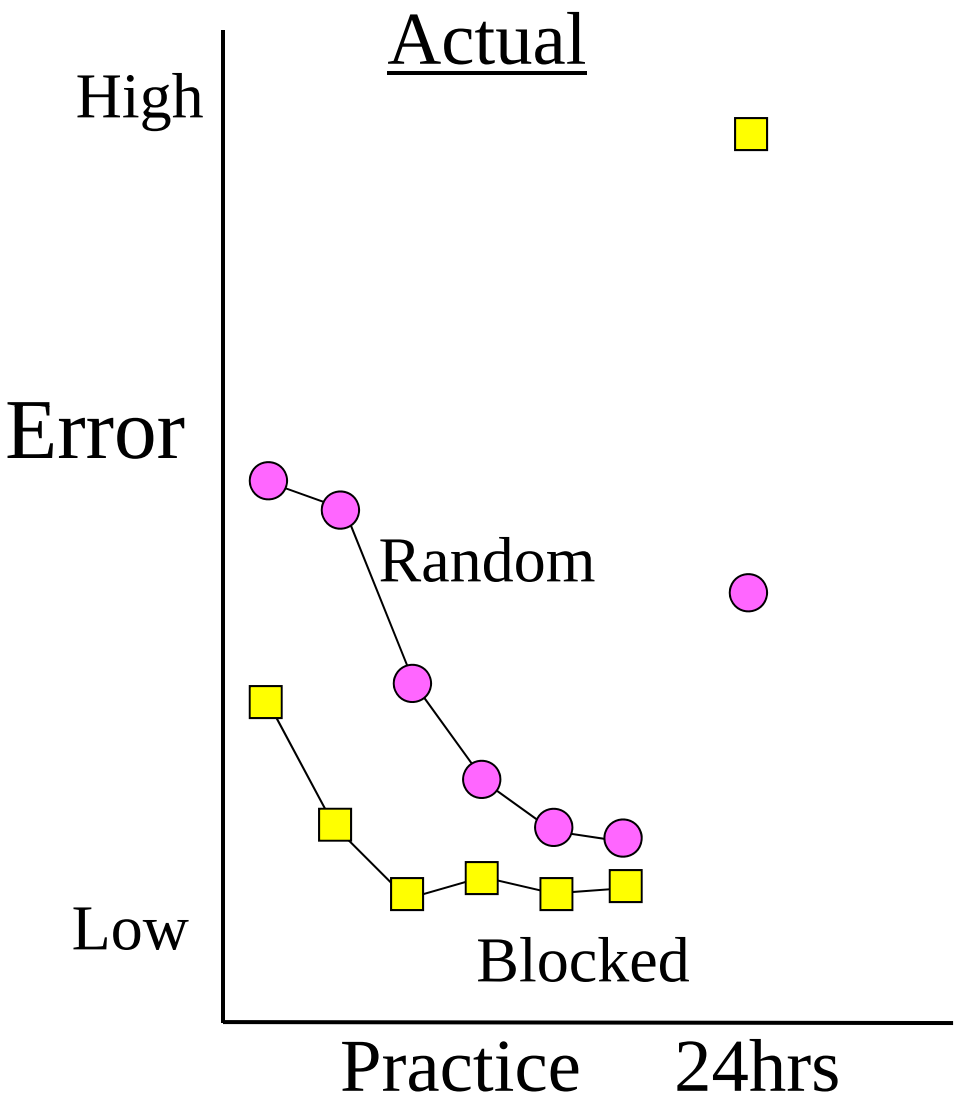
participant responds
plus
2-second delay

5 seconds

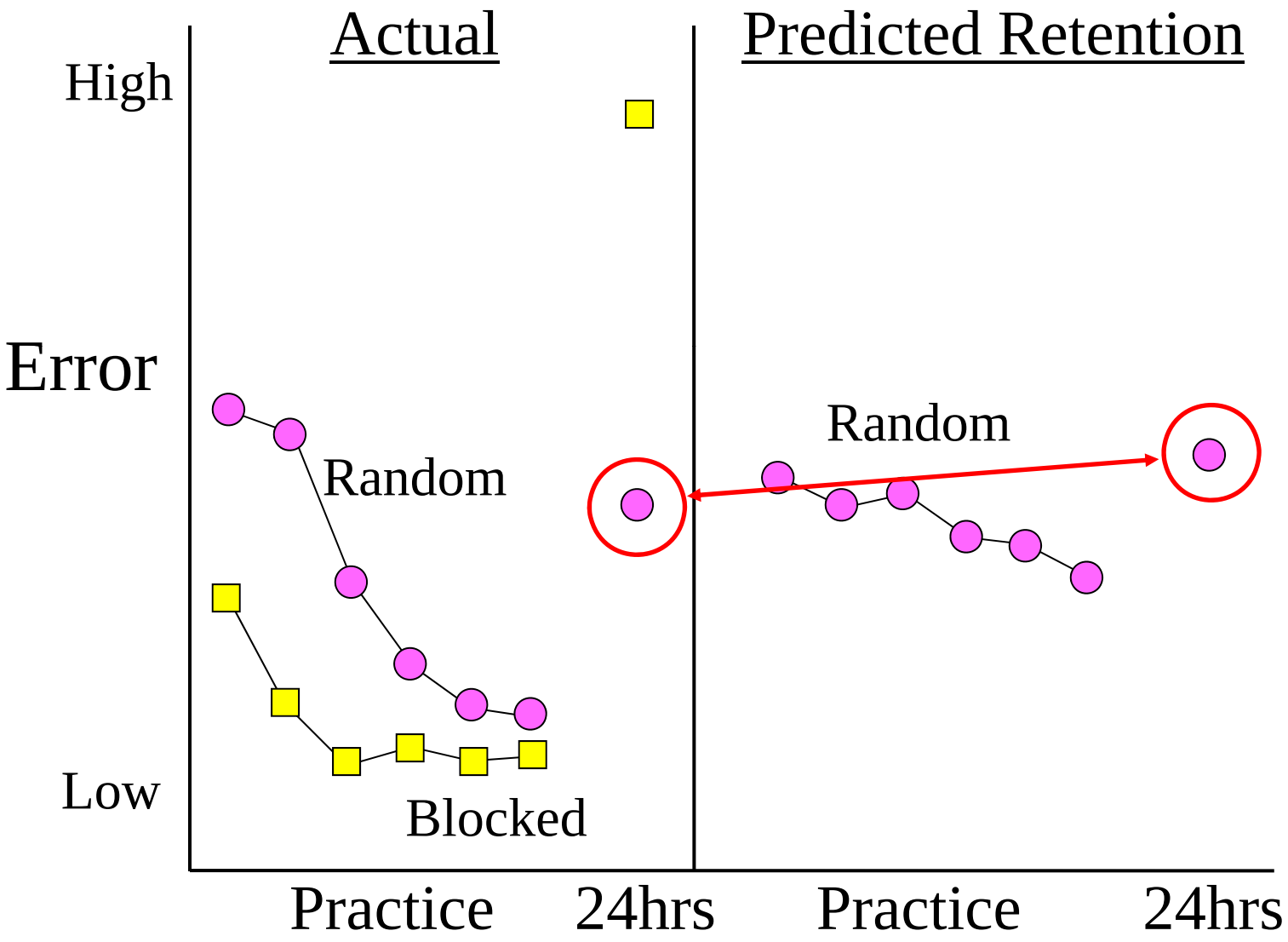
keys were correct
MT (ms): 840
You were 60 ms too fast

1 second

Simon & Bjork (2001)



Simon & Bjork (2001)



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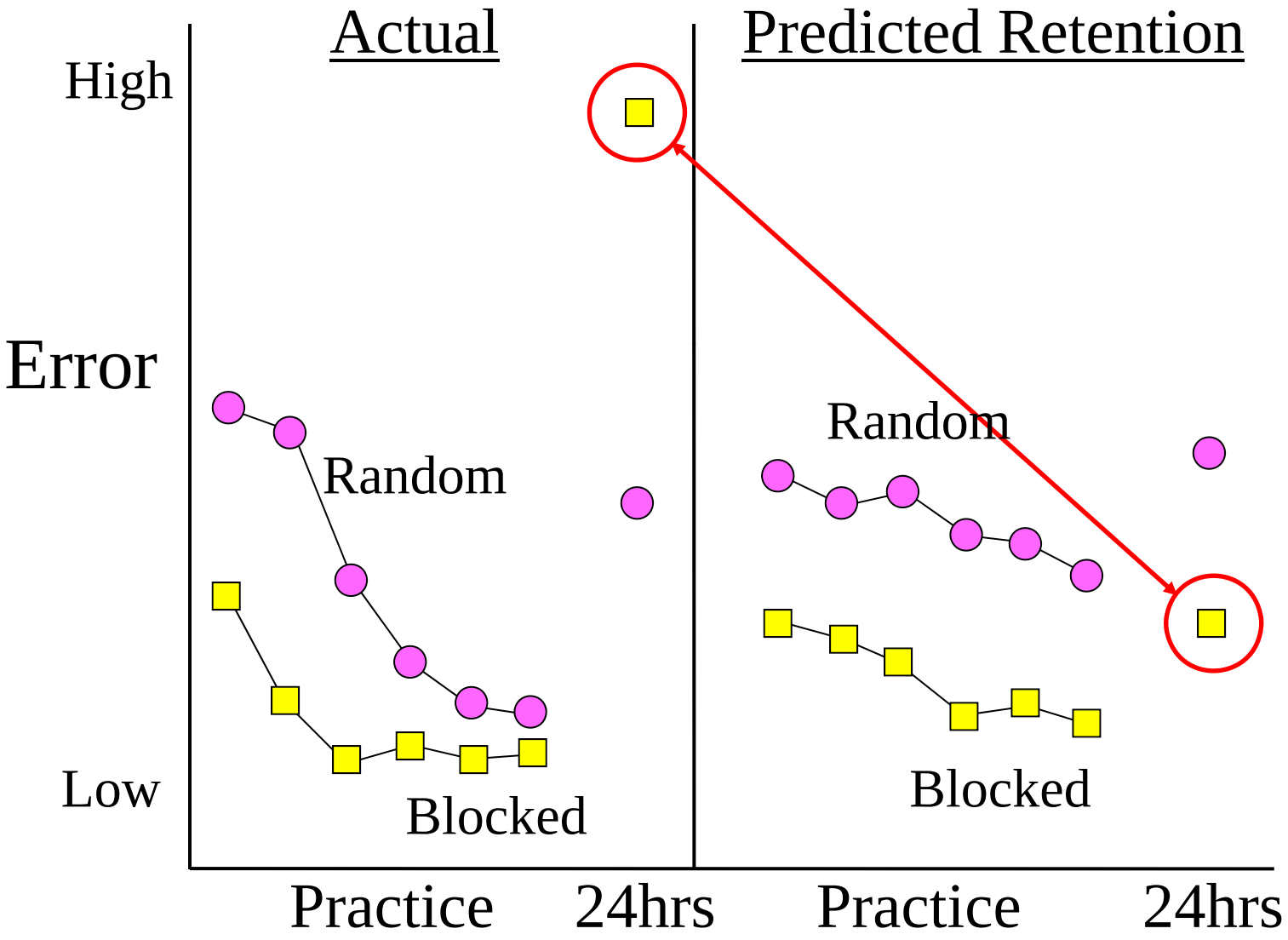


Jamieson & Rogers (2000)

- Learn bank transaction operations (withdrawal, deposit, transfer, account info) on a simulated (ATM)
- Practice conditions:
  - Blocked: blocks of 5 similar transactions (withdraw $100 from checking; withdraw $60 from savings, etc.)
  - Random/interleaved: Each block included 5 different types of transactions
- Transfer tests:
  - Near transfer: similar transactions on same ATM;
  - Far transfer: novel transactions on different ATM

ATM transactions

Table 3. Sample Transactions

Experiment Phase	Simulator	Sample Transaction
Acquisition[a]	ATM1	Withdraw $25 using Fast Cash
		Withdraw $100 from checking
		Transfer $300 to savings from checking
		Deposit $200 cash into line of credit
		Get balance on checking
Near transfer	ATM2	Withdraw $25 using Fast Cash
		Withdraw $100 from checking
		Transfer $300 to savings from checking
		Deposit $200 cash into line of credit
		Get balance on checking
Far transfer	ATM2	Get price per ounce on gold exchange
		Buy 3 Frank Sinatra tickets with credit card
		Pay $200 on electric bill with cash
		Buy a Lotto ticket with savings
		Pay $100 cable TV bill with credit card

[a]There were 50 total transactions during acquisition.

ATM1

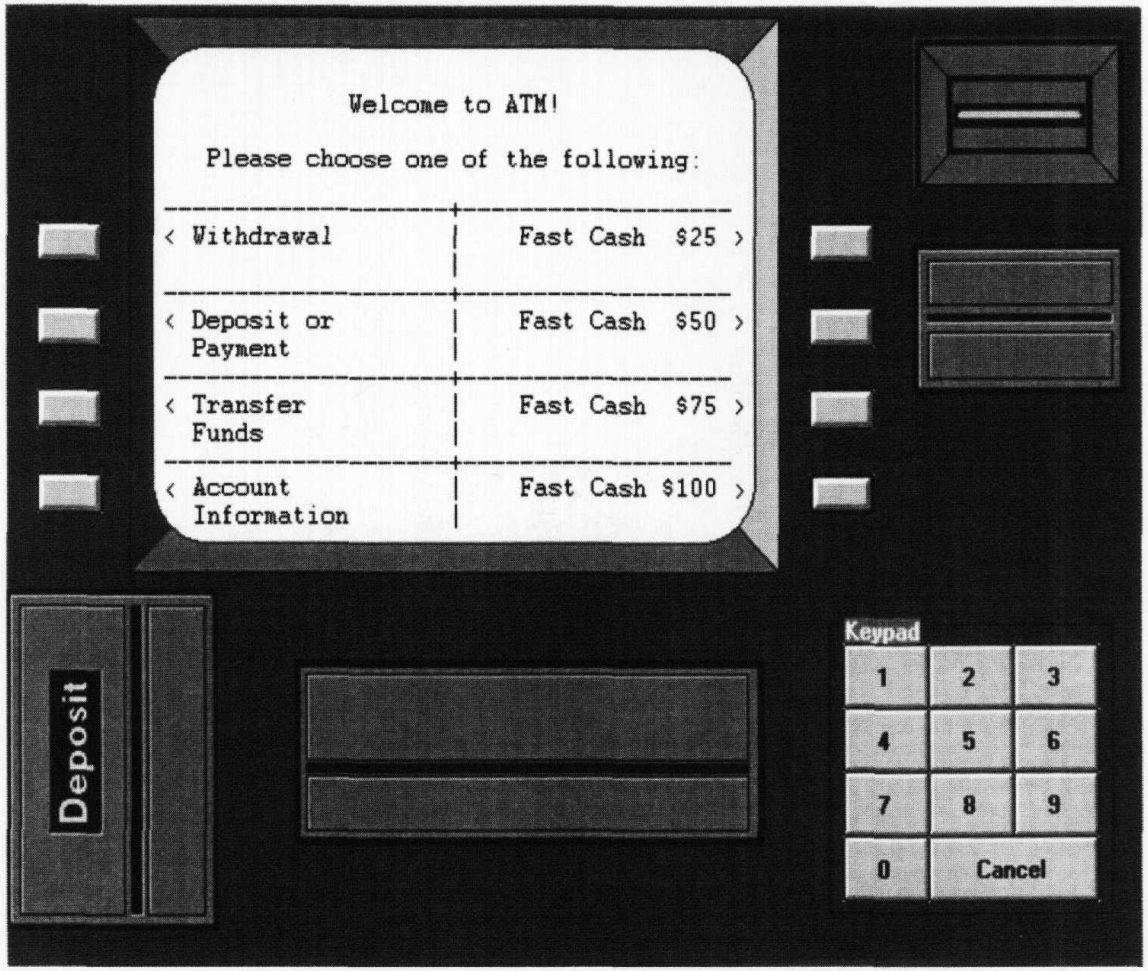


Figure 1. Illustration of the first screen of automatic teller machine simulator version 1 (ATM1). This simulator was modeled after an existing ATM. The background screen was gray and the menu options text was green.

ATM2

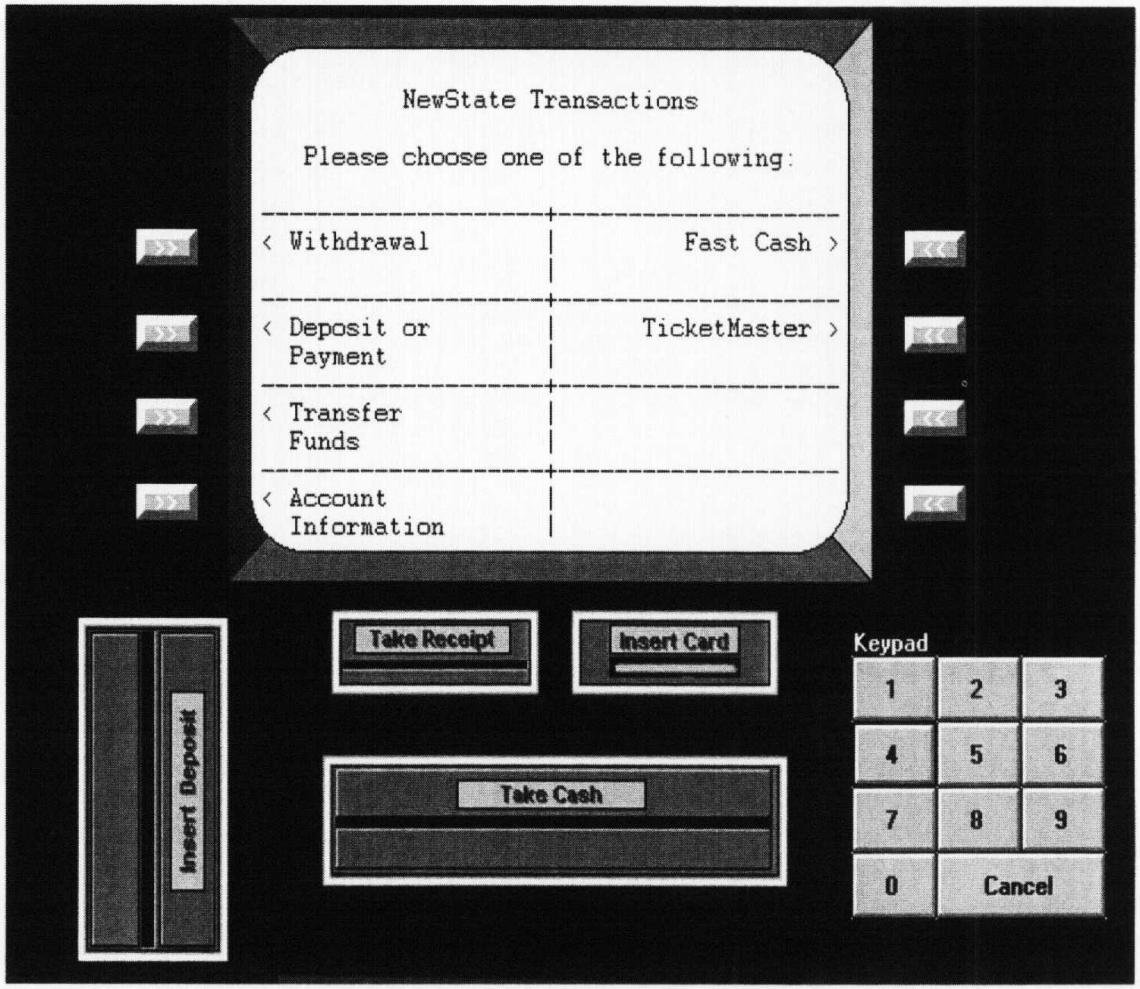
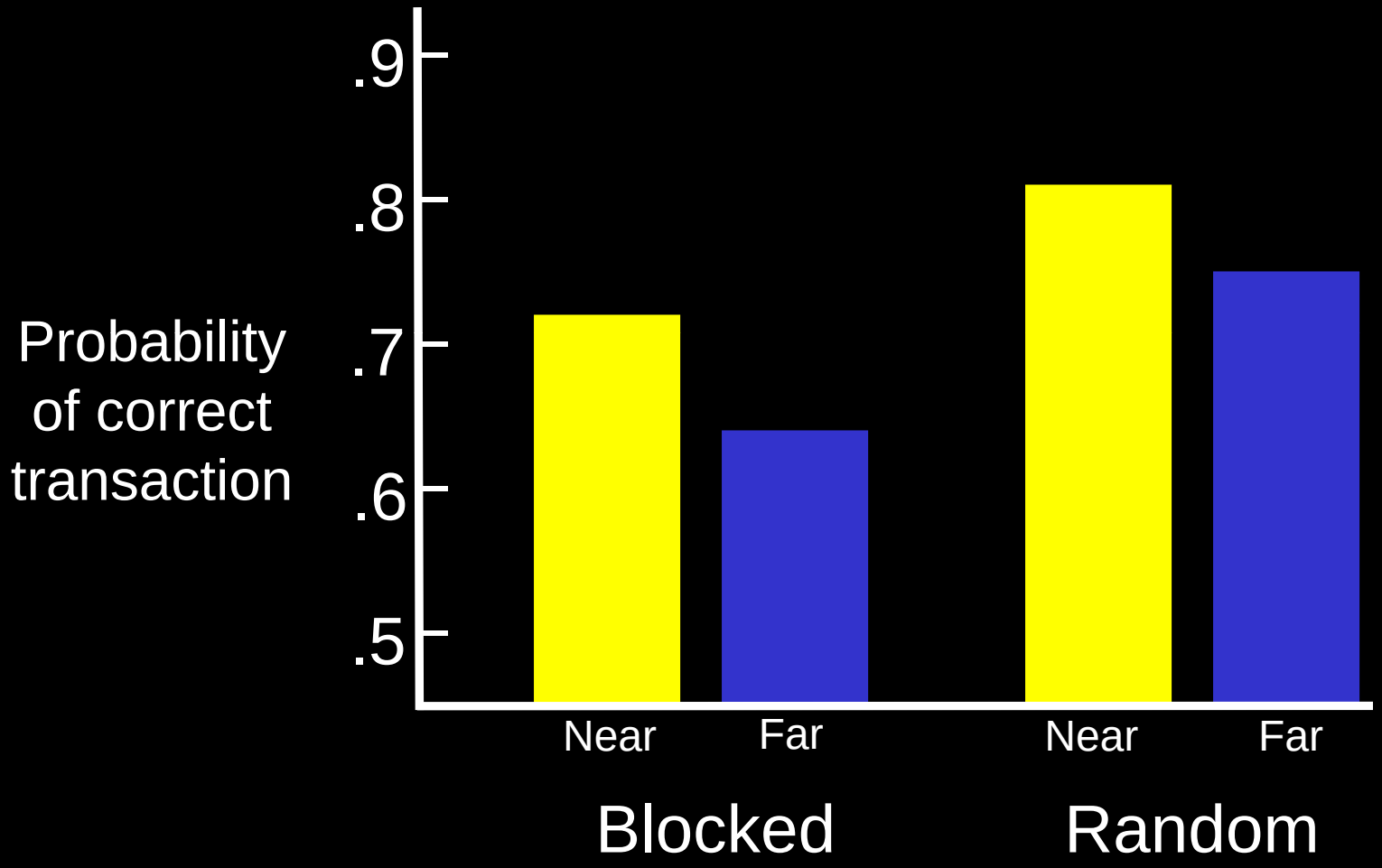
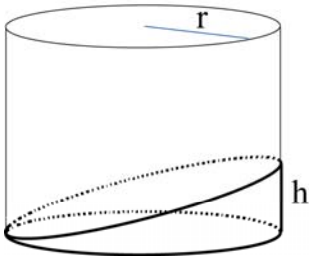


Figure 2. Illustration of the first screen of automatic teller machine simulator version 2 (ATM2). This simulator differed from ATM1 in several ways: different menu structure, options that were not available on ATM1, different surface layout, and the background screen was blue with yellow menu options text.

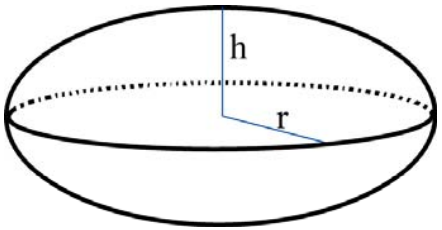
Results (Jamieson & Rogers, 2000)



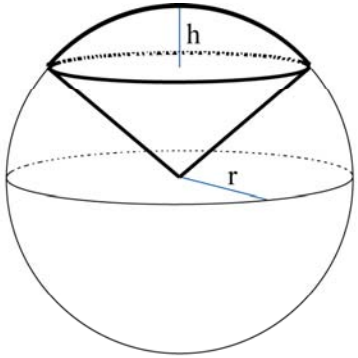
Rohrer & Taylor (2007)



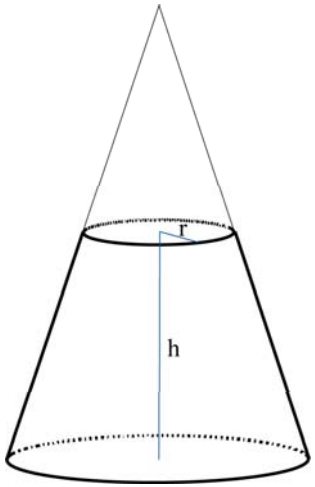
Wedge V= $\frac{r^2 h \pi}{2}$



Spheroid V= $\frac{4 r^2 h \pi}{3}$



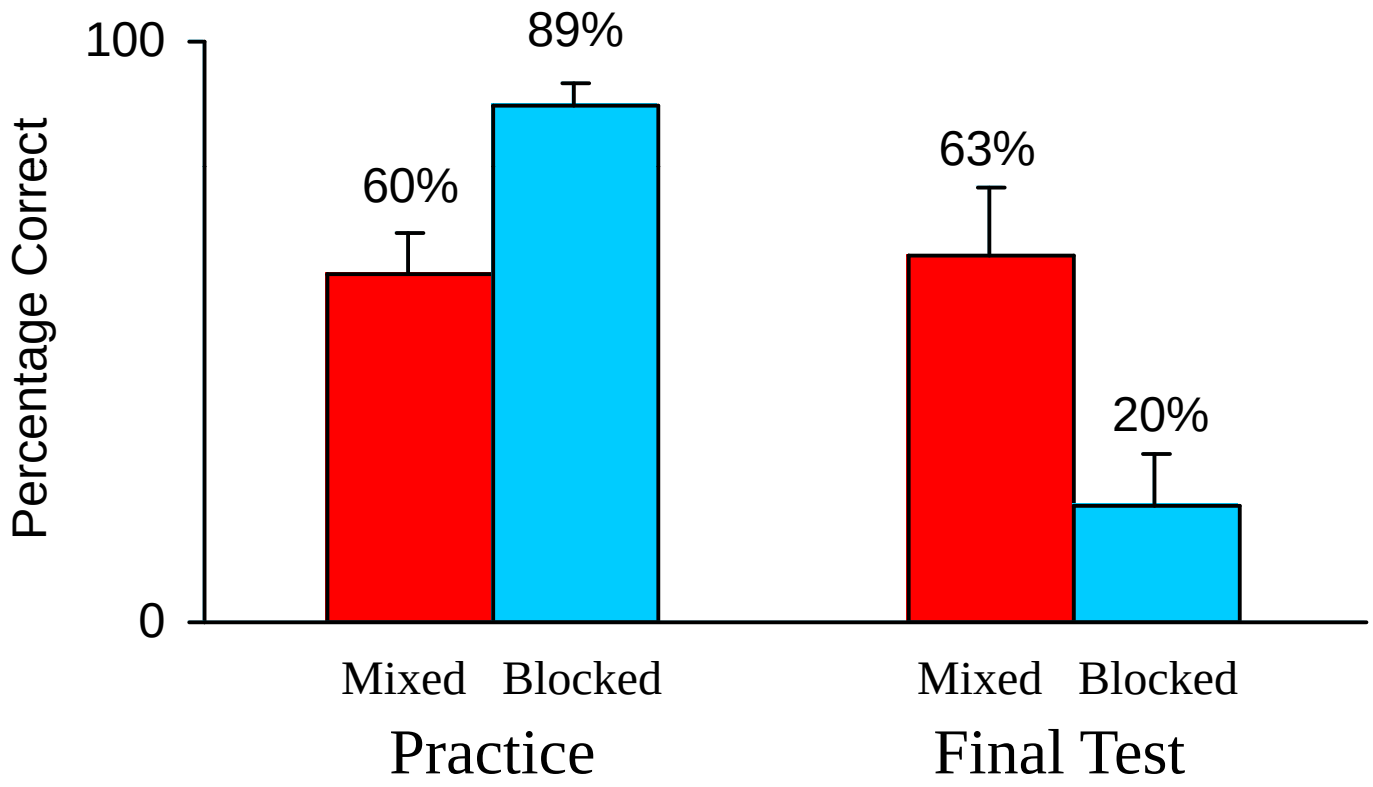
Spherical Cone V= $\frac{2 r^2 h \pi}{3}$



Half Cone V= $\frac{7 r^2 h \pi}{3}$

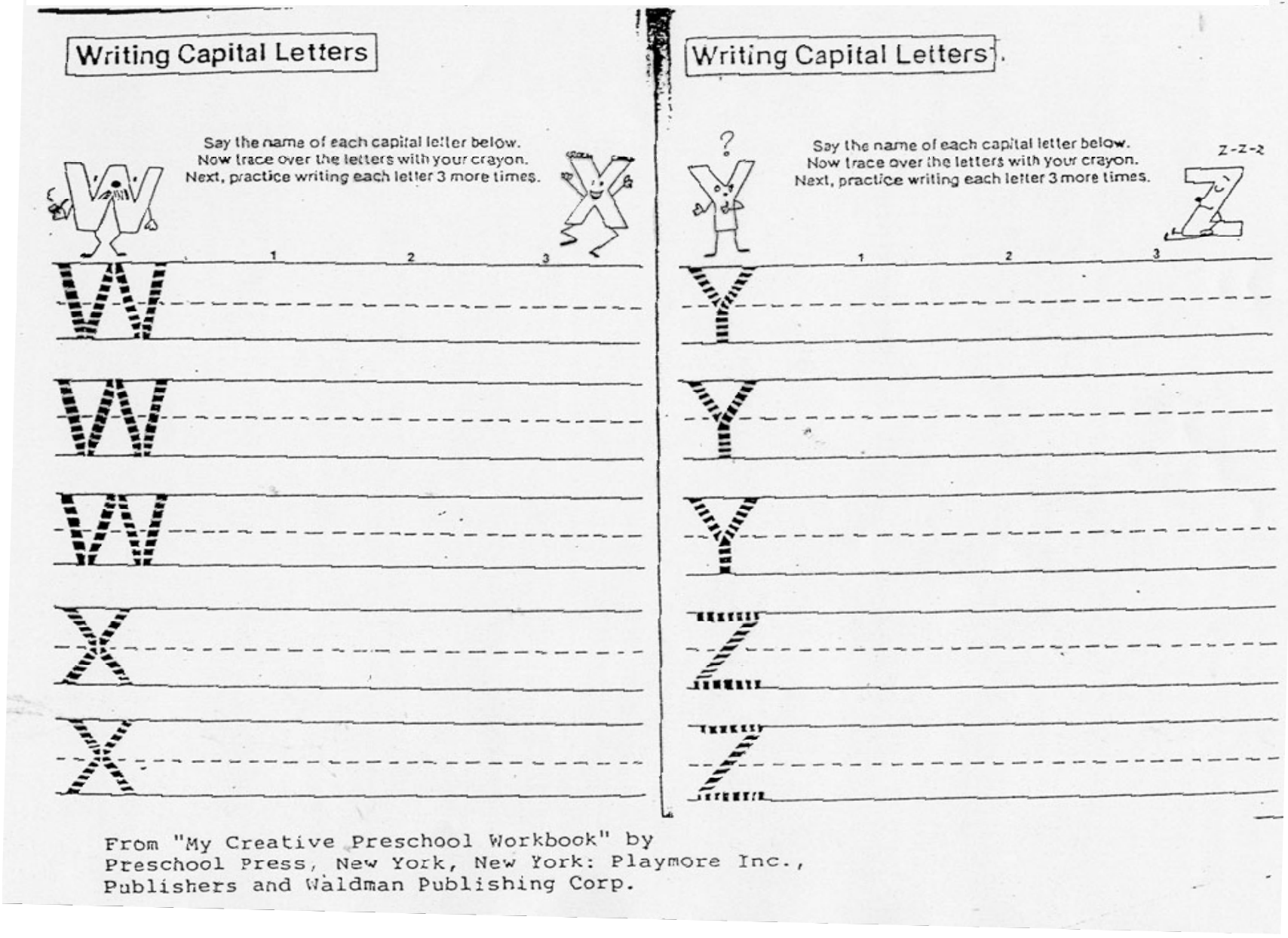
Procedure (Rohrer & Taylor, 2007)

- Undergraduate participants read 4 tutorials and worked 16 problems, 4 of each type.
  - Participants had 40s to work each problem, followed by a 10-sec presentation the solution.
  - **Mixers:** Read all 4 tutorials before working 16 randomly arranged problems.
  - **Blockers:** Each tutorial was immediately followed by 4 problems of that type.
- Participants tested one week after the learning session.
  - Two problems on each type of solid intermingled.
  - None of the test items appeared during the practice phase.


100
0
Percentage Correct
89%
60%
63%
20%
Mixed
Blocked
Mixed
Blocked
Practice
Final Test

Blocked versus interleaved practice

Ste-Marie, Clark, Findlay, & Latimer (2004)



Writing Capital Letters

Say the name of each capital letter below.
Now trace over the letters with your crayon.
Next, practice writing each letter 3 more times.

1 2 3

W

W

W

X

X

Writing Capital Letters

Say the name of each capital letter below.
Now trace over the letters with your crayon.
Next, practice writing each letter 3 more times.

Z-Z-Z

1 2 3

Y

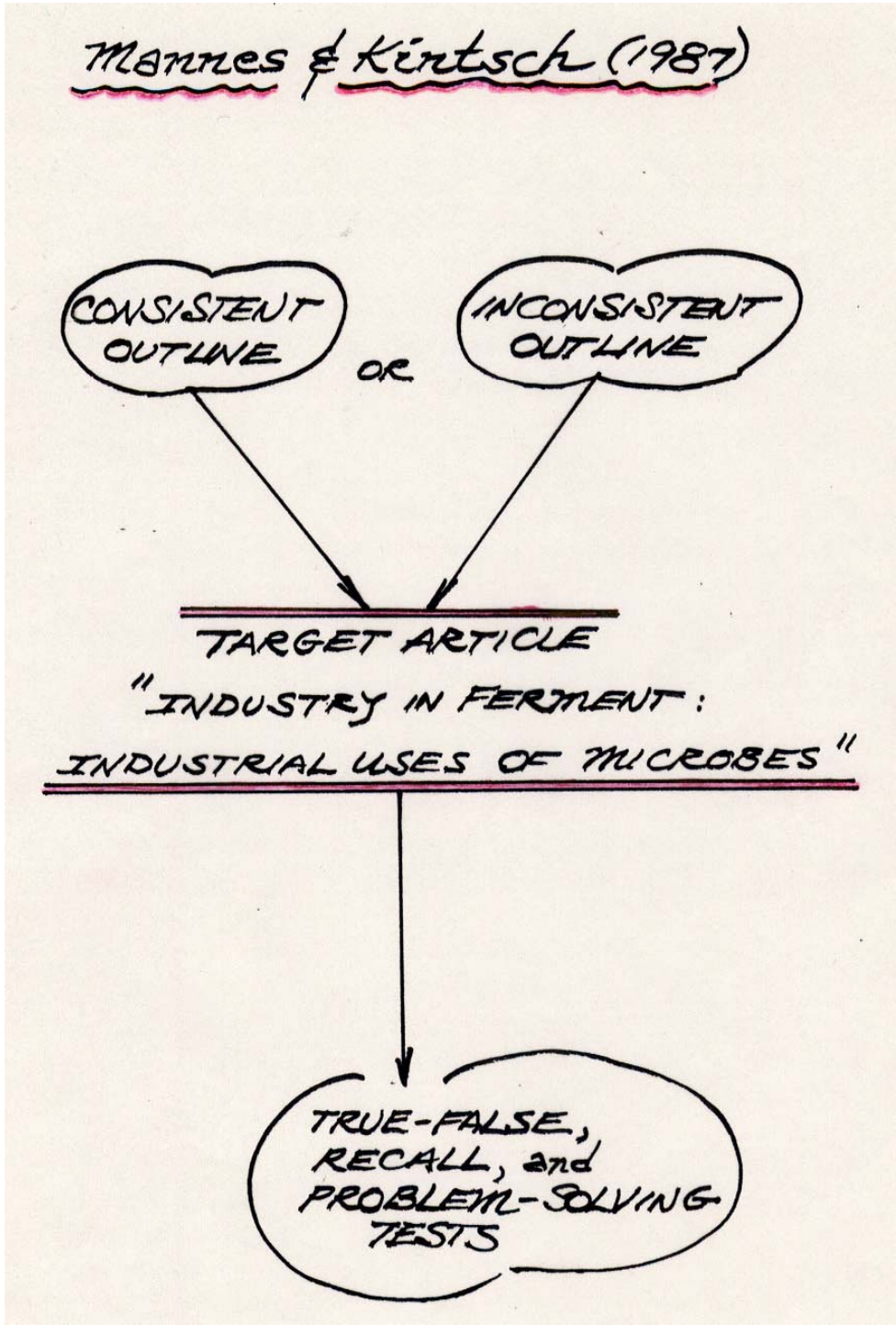
Y

Y

Z

Z

From "My Creative Preschool Workbook" by
Preschool Press, New York, New York: Playmore Inc.,
Publishers and Waldman Publishing Corp.


Mannes & Kintsch (1987)
CONSISTENT OUTLINE
OR
INCONSISTENT OUTLINE
TARGET ARTICLE
"INDUSTRY IN FERMENT:
INDUSTRIAL USES OF MICROBES"
TRUE-FALSE, RECALL, and PROBLEM-SOLVING TESTS

(Mannes & Kintsch, 1987)

Microbes

Although yeasts, molds, and bacteria don't require timecards or contracts, organizing them for factory-scale jobs is complicated and expensive. Microbes have been making beer and wine and bread and cheese for millennia. But it wasn't until 1912, more than four decades after their role in fermentation was finally understood, that bugs were put to work outside the food business.

That year Chaim Weizmann, a Russian chemist living in England who later became the first president of Israel, discovered a method for making butanol, a kind of alcohol. Weizmann used two species of Clostridium bacteria, one feeding on sugar and the other on starch, to make not only butanol but acetone. World War I helped create a ready market for these chemicals; butanol is used in the manufacture of synthetic rubber, and acetone is essential for making cordite, an explosive. But when peace returned, there was little demand for cordite, and eventually butanol became cheap to make from petrochemicals.

Today, with the major exception of the production of pharmaceuticals, industrial-scale fermentation is again largely confined to the manufacture of foods and beverages. Most of the things microbes can make are cheaper to produce synthetically, in particular by petrochemical processes that owe nothing to biology except the ultimate source of their raw materials, fossil fuels. But the range of things natural microorganisms could help produce is enormous: fuels, dyes, vitamins, the chemical precursors essential to the manufacture of everything from plastics to pesticides and thousands of other products.

Both economic and technical problems conspire to keep bugs from working as hard as they could. The complex business of taking a successful laboratory procedure off the bench and into the factory is called scaling up. And it applies equally to devising a process for making human pharmaceuticals a few grams at a time or to devising a thriftier means of producing inexpensive organic acids by the ton.

If biotechnology is to compete with the petrochemical industry, says Chaning Robertson, Stanford professor of chemical engineering, merely increasing the size of tanks and pipes is not the answer. Biochemical plants must be able to produce the same concentration of a given product in roughly the same amount of time. "In the traditional processes I looked at," says Robertson, "the productivities were orders of magnitude less than the typical petrochemical facility. You certainly wouldn't want to build a biochemical plant that was 10,000 times bigger." The size of even a small fermentation vat-a bioreactor in the jargon of the trade-is enormous compared to the modest quantities of chemical finally extracted.

So one major goal of biochemical engineers is to miniaturize the hardware wherever possible. Bioreactors vary from something the size of a beer keg to something looking more like a municipal water tank. Inside, vigorously stirred by paddles to keep the fermenting broth well blended, the bugs seethe and multiply into billions. A maze of

MICROBES CAN MAKE ANYTHING

I. MICROBES
A. MICROORGANISMS CAN BE USED TO MAKE A POTENTIALLY LARGE NUMBER OF THINGS.
1. NATURALLY
A. THEORETICALLY, BUGS (MICROBES) CAN BE CHOSEN TO PRODUCE VIRTUALLY ANY SUBSTANCE ANY CELL MARES NATURALLY AND SOME THEY DO NOT.
B. THEY HAVE BEEN USED TO MAKE WINE, BEER, CHEESE, AND BREAD FOR MANY YEARS.
C. BACTERIA ARE REGARDED AS THE SIMPLEST FORMS OF YEAST AND MOLD CONTAINING NO CHLOROPHYLL.
D. MOST SPECIES OF BACTERIA ARE NOT PATHOGENIC (DISEASE CAUSING) AND ARE IN NO WAY RELATED TO INFECTION (ALTHOUGH THERE ARE MANY SPECIES OF BACTERIA WHICH CAN ALTER OR DESTROY PLANTS AND ANIMALS WHICH MAN ENJOYS OR DEPENDS ON AND WHICH CAUSE DISEASE, OFTEN FATAL TO MAN HIMSELF. THESE ARE STUDIED MORE OFTEN THAN OTHER TYPES)
2. ARTIFICIALLY-MORE RECENTLY HAVE BEEN PROMPTED USING METHODS SUCH AS RECOMBINANT DNA 10 MAKE CHEMICALS LIKE BUTANOL AND ACETONE. THIS PRODUCTION IS OFTEN ACCOMPLISHED IN VATS WHERE, THE BItS SEETH AND MULTIPLY INTO BILLIONS AS THEY ARE VIGOROUSLY STIRRED BY PADDLES TO KEEP THE MIXTURE OF BUGS WELL BLENDED. BUGS LIKE BACTERIA BRING THINGS IN AND MIX THEN UP WITHIN THEMSELVES MAKING A PRODUCE IN THE PROCESS.
B. AS HO OTHER FORMS OF LIFE, BACTERIA REQUIRE WATER, MINERALS, VITAMINS AND SOURCES OF CARBON AND NITROGEN FOR GR(3'TH AND BACTERIA CONVENIENTLY CAN BE CLASSIFIED INTO THREE MAJOR GROUPS ACCORDING TO THE MATERIALS THEY EMPLOY AS SOURCES OF ENERGY. SOME USE ORGANIC COMPOUNDS, SOME UTILIZE RADIANT ENERGY AND STILL OTHERS OXIDIZE INORGANIC MOLECULES.
1. UNDER CONDITIONS FAVORABLE TO GROWTH, BACTERIA MULTIPLY IN GEOMETRIC PROGRESSION: 2,4,8,16,32,64 WHEN FIRST TRANSFERRED '10 A FAVORABLE ENVIRONMENT, THERE IS A PERIOD OF ADJUSTMENT, FOLLOWED BY A MULTIPLICATION OF SOME CELLS, THEN OF NEARLY ALL CELLS, AND THEN A GRADUAL SLOWING DONN OF MULTIPLICATION UNTIL FINALLY THERE IS NO NET INCREASE. DURING THIS TIME, BACTERIA HAVE ENLARGED AND DIVIDED MANY TIMES, PRODUCED VARIOUS ENZYMES, CHANGED SOME OF THE CHEMICAL OF THEIR ENVIRONMENT, AND ABSORBED SOME SUBSTANCES ALREADY PRESENT OR FORMED.
2. NEARLY ALL KNOWN ENZYMES ARE PRODUCED BY ONE OR ANOTHER KIND OF BACTERIA AND MANY NOT KNOWN OUTSIDE OF BACTERIOLOGY (THE STUDY OF BACTERIA) AR FORMED.
3. THESE BUGS HAVE NOT BEEN ALLOWED '10 DO AS MUCH AS THEY ARE CAPABLE OF BECAUSE OF ECONOMICAL AND TECHNICAL REASONS. FOR ONE THING, ORGANIZING MICROBES FOR FACTORY-SCALE JOBS CAN BE VERY EXPENSIVE AND PRODUCTS CAN OFTEN BE MADE SYNTHETICALLY MUCH CHEAPER THAN BY ENLISTING MICROORGANISMS. TECHNICALLY, ORGANIZING MICROBES FOR FACTORY-SCALE WORK IS QUITE COMPLICATED.
C. NATURAL VS WILD
1. NATURAL OR WILD ORGANISMS ARE MUCH STURDIER THAN THE ONES CREATED WITH RECOMBINANT TECHNIQUES.
A. THE WILD BUGS TOLERATE A WIDER RANGE OF ENVIRONMENTAL CONDITIONS AND TEMPERATURES. IN FACT THE FEEBLE RECOMBINANTS NEED TO BE CODDLED IN AN ENVIRONMENT MORE LIKE A REST HOME THAN A FACTORY.
B. WILD MICROBES THRIVE AT ROOM TEMPERATURE, THEY REPLACE THEMSELVES FASTER THAN THEY WEAR OUT AND THEY ARE NOT PICKY EATERS.

CHARACTERISTICS OF MICROBES

I. BACTERIA ARE REGARDED AS THE SIMPLEST FORMS OF YEAST AND MOLD CONTAINING NO CHLOROPHYLL.

II. BACTERIA CAN BE *CLASSIFIED ACCORDING* TO FOUR CHARACTERISTICS

A. MICROSCOPIC APPEARANCE AND STAINING REACTION (MORPHOLOGY)

1. MOST BACTERIAL FORMS RANGE IN SIZE FROM .5 TO 10 MICRONS IN LENGTH. A MICRON .001 MILLIMETER.
2. MORPHOLOGICALLY (IN FORM AND STRUCTURE), BACTERIA FALL INTO 4 CATEGORIES.
    A. APPROXIMATELY SPHERICAL-COCCUS
    B. ROD OR CYLINDRICAL-BACILLUS
    C. RIGID COILED ROD-SPIRILI
    D. FLEXIBLE HAIRLIKE-SPIROCHETE
3. COLONIES OF BACTERIA MAY BE TRANSLUCENT (CLEAR) OR OPAQUE; WHITE, VIOLET, YELLOW, OR COLORLESS ;SHINY OR DULL;AND VISCOUS, PASTY OR CRUMBLY IN CONSISTENCY.

B. PHYSIOLOGICAL CHARACTERISTICS (PRESENCE OF SPECIFIC PROTEINS AND CARBOHYDRATES)

1. BACTERIA CONTAIN NOT ONE BUT MANY ANTIGENS. ANTIGENS ARE ORDINARILY COMPLEX SUBSTANCES, WITH OR WITHOUT CARBOHYDRATES.
2. DIFFERENT SPECIES OF BACTERIA MAY HAVE ANTIGENS IN COMMON BUT IT IS NOT CLEAR TO WHAT EXTENT THIS SHOULD BE A BASIS FOR DEFINING A SPECIES, OR TO WHAT EXTENT IT SUBDIVIDES A SPECIES.

C. APPEARANCE OF GROWTH ON THE SURFACE OF SOLID MEDIA OR LIQUID MEDIA (METABOLISM)

1. BUGS LIKE BACTERIA BRING THINGS IN AND MIX *TEEM UP* WITHIN THEMSELVES MAKING A PRODUCT IN THE PROCESS. UNDER CONDITIONS FAVORABLE TO GROWTH, BACTERIA MULTIPLY IN GEOMETRIC PROGRESSION: 2,4,8,16,32,64 WHEN FIRST TRANSFERRED TO A FAVORABLE ENVIRONMENT, THERE IS A PERIOD OF ADJUSTMENT, FOLLOWED BY A MULTIPLICATION OF SOME CELLS, THEN OF NEARLY ALL CELLS (THEY REPLACE THEMSELVES FASTER THAN THEY WEAR OUT), AND THEN A GRADUAL SLOWING DOWN OF MULTIPLICATION UNTIL FINALLY THERE IS NO NET INCREASE. DURING THIS TIME, BACTERIA HAVE ENLARGED AND DIVIDE!) MANY TIMES, PRODUCED VARIOUS ENZYMES, CHANGED SOME OF THE CHEMICALS OF THEIR ENVIRONMENT, AND ABSORBED SOME SUBSTANCES ALREADY PRESENT OR FORMED.

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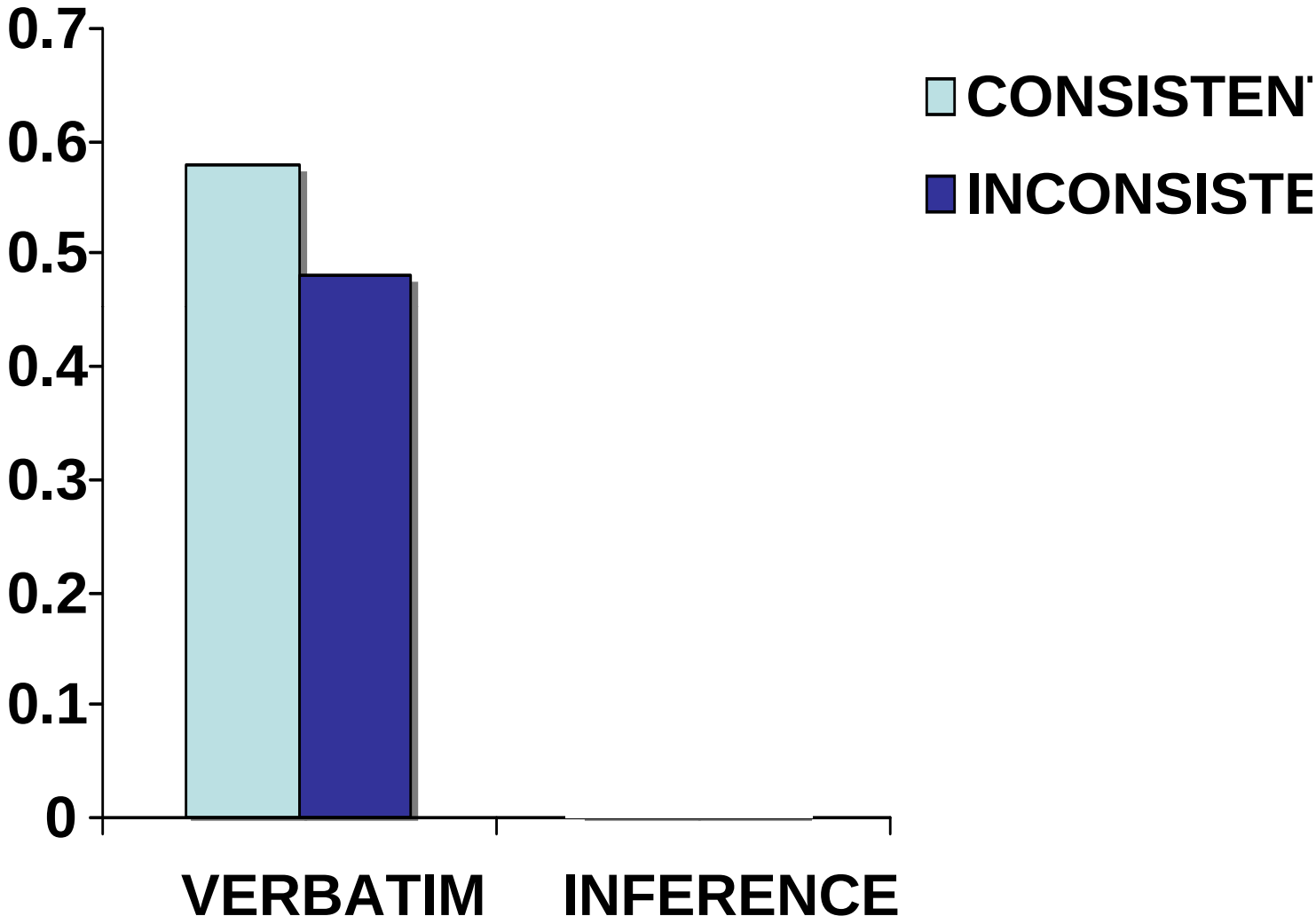
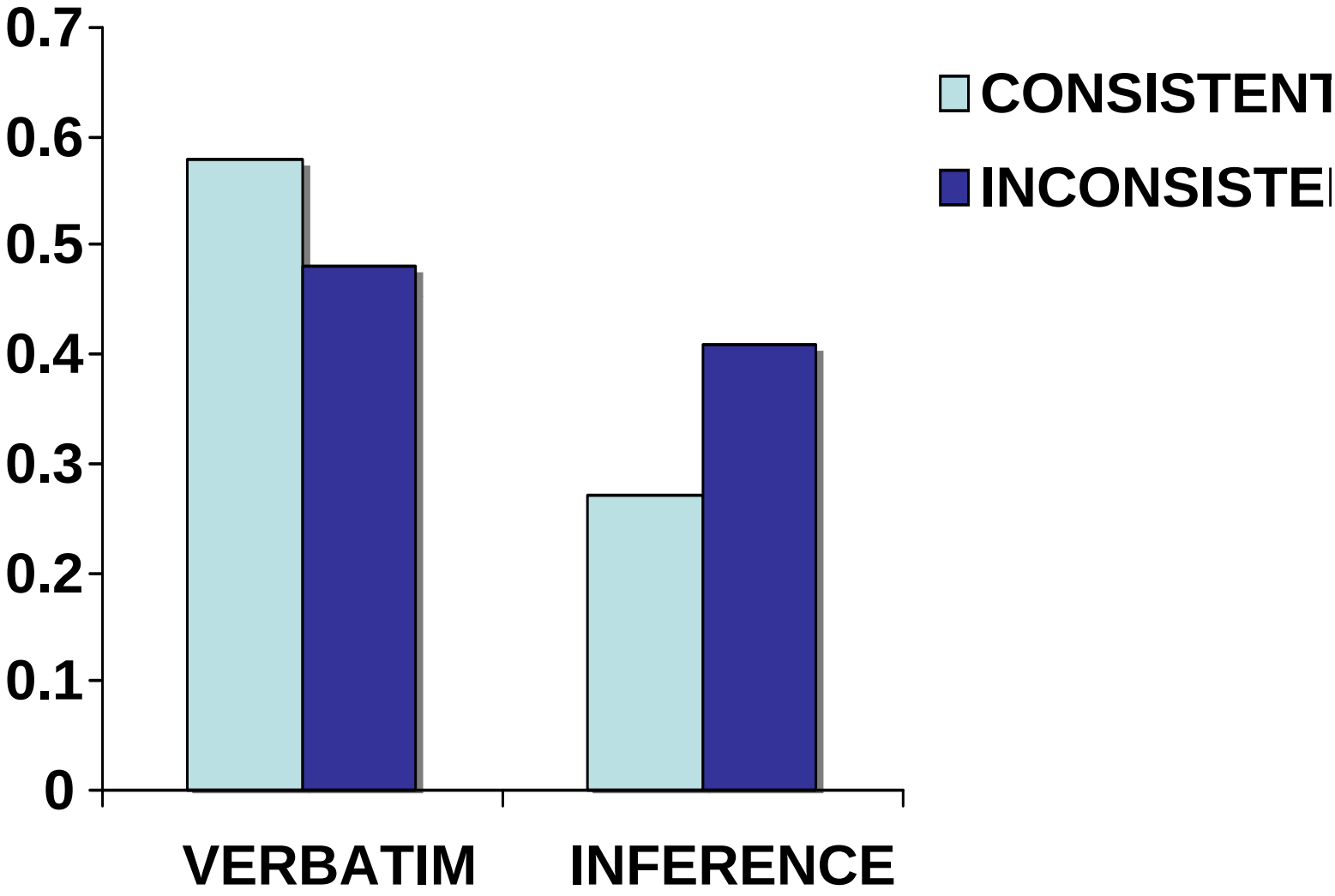
Mannes & Kintsch (1987)

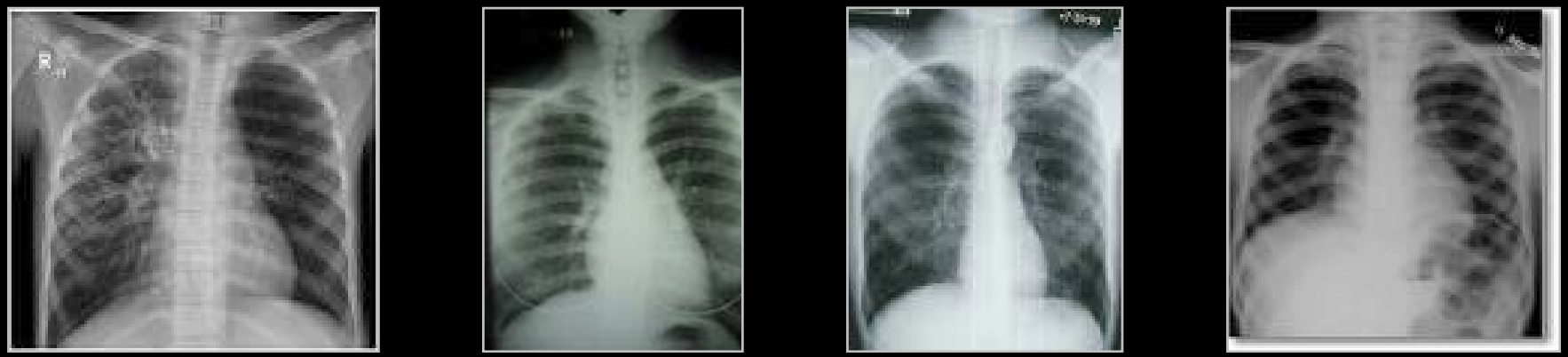


Mannes & Kintsch (1987)



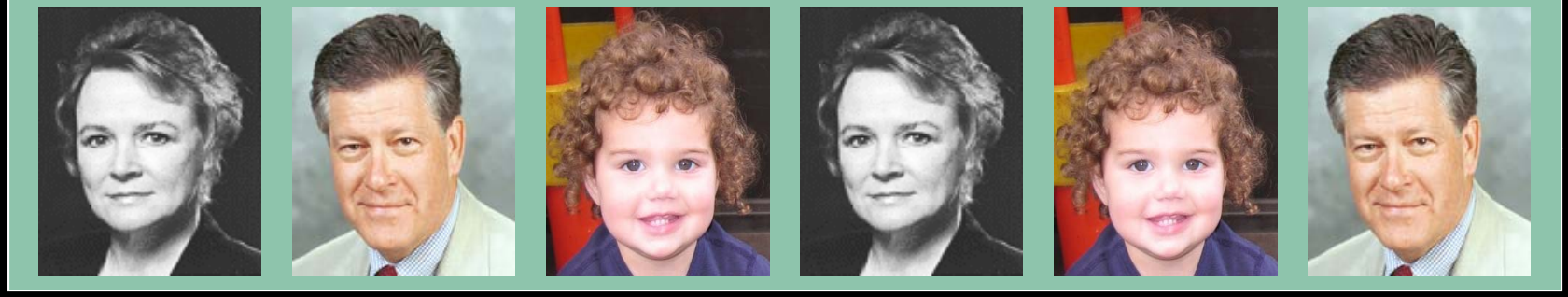
Optimizing induction

- The ability to generalize concepts and categories through exposure to multiple exemplars.



Interleaving/spacing versus blocking/massing

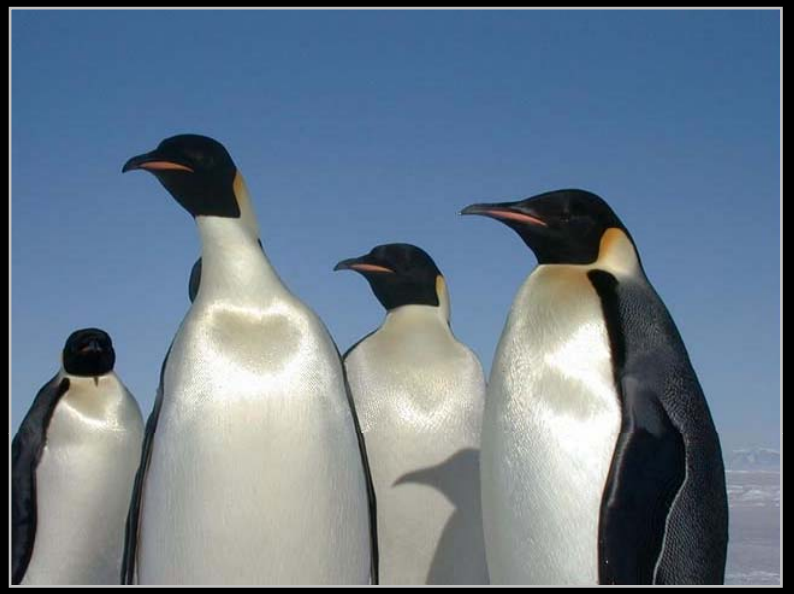
Interleaved/spaced: items re-studied after other items



Blocked/massed: items studied in succession

Gentoo

Where’s the Gentoo?



Hypothesis

- Blocking/massing allows the learner to notice characteristics that unify a category


Gentoo


Gentoo


Gentoo


Gentoo

- Interleaving/spacing makes doing so difficult


Gentoo


Lachesis


Reinhard


Gentoo

"Spacing is the friend of recall but the enemy of induction."

-Ernst Rothkopf

Method: Kornell and Bjork (2008, *Psychological Science*)

1. Instructions
2. Study
3. Distractor
4. Test
5. Questionnaire

Instructions

In this experiment you're going to look at some beautiful paintings. To start, you'll be shown 72 paintings for 3 seconds each. The paintings will be by twelve artists, with six pictures per artist. Try to learn to recognize which artist painted which picture based on their style.

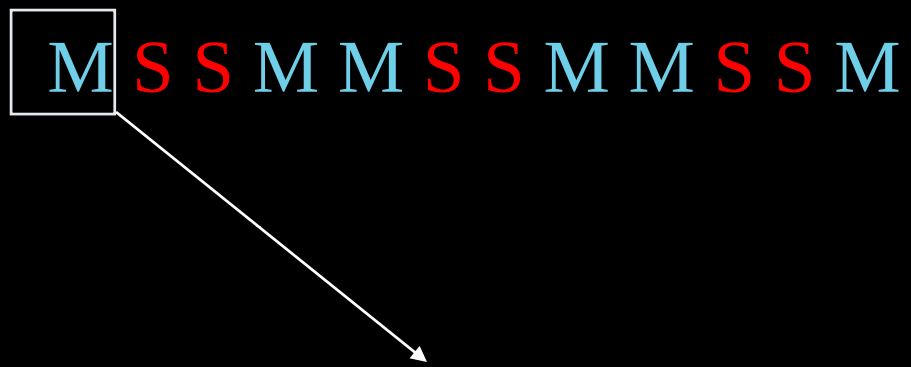
Later, you'll be shown 48 new paintings, which you haven't seen before. You'll have to identify who painted each one.

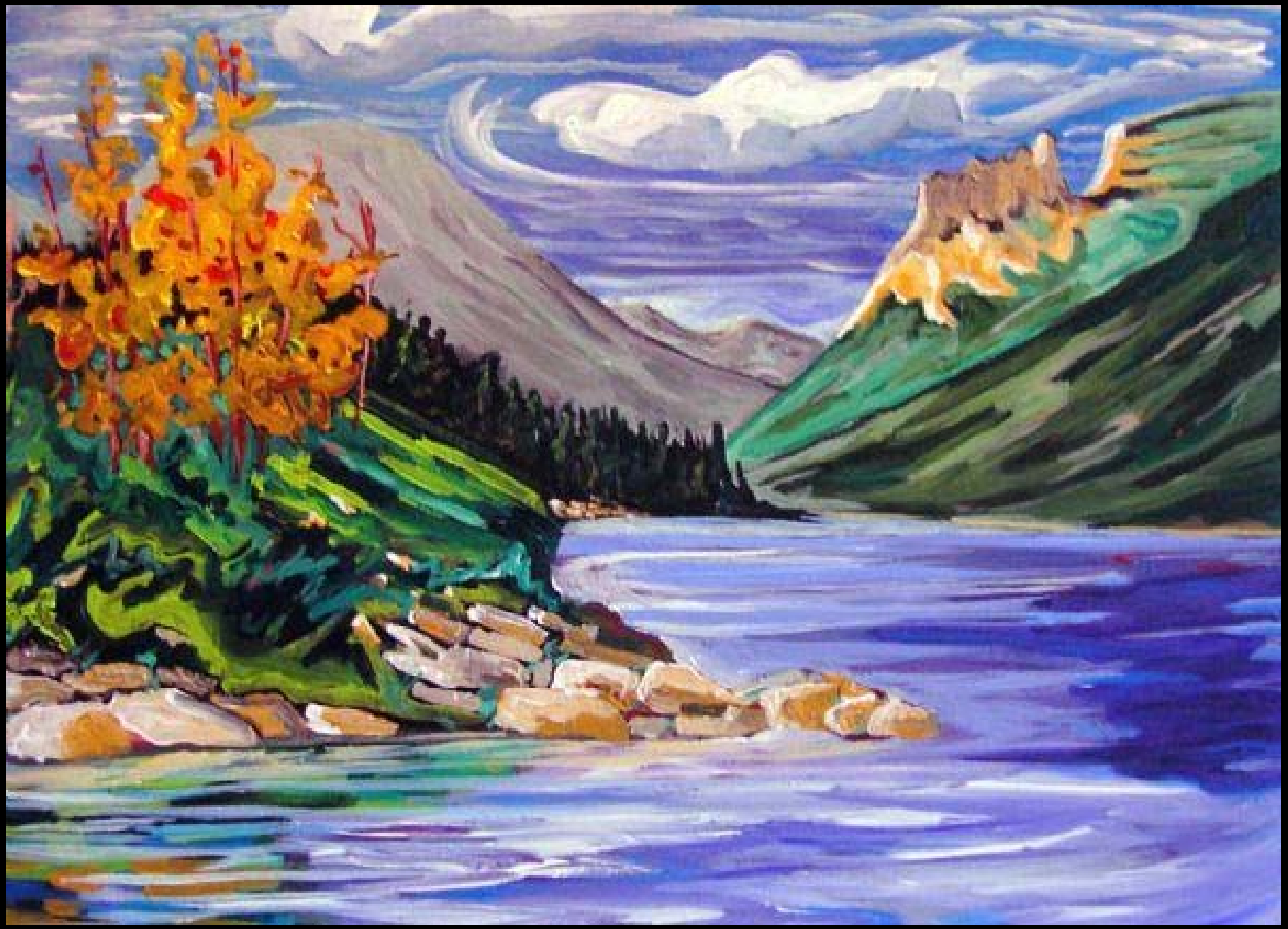
For example, if there were only two artists, named Al and Barb, you'd be shown paintings by Al and Barb, and later, you'd be shown new paintings and asked who painted them, Al or Barb.

Design

- Two within-subject conditions: massed & spaced

M S S M M S S M M S S M


M S S M M S S M M S S M
Massed block



Lewis

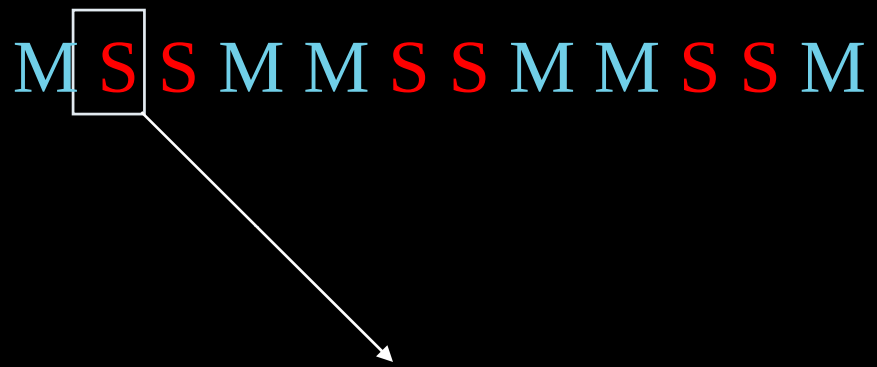
Lewis

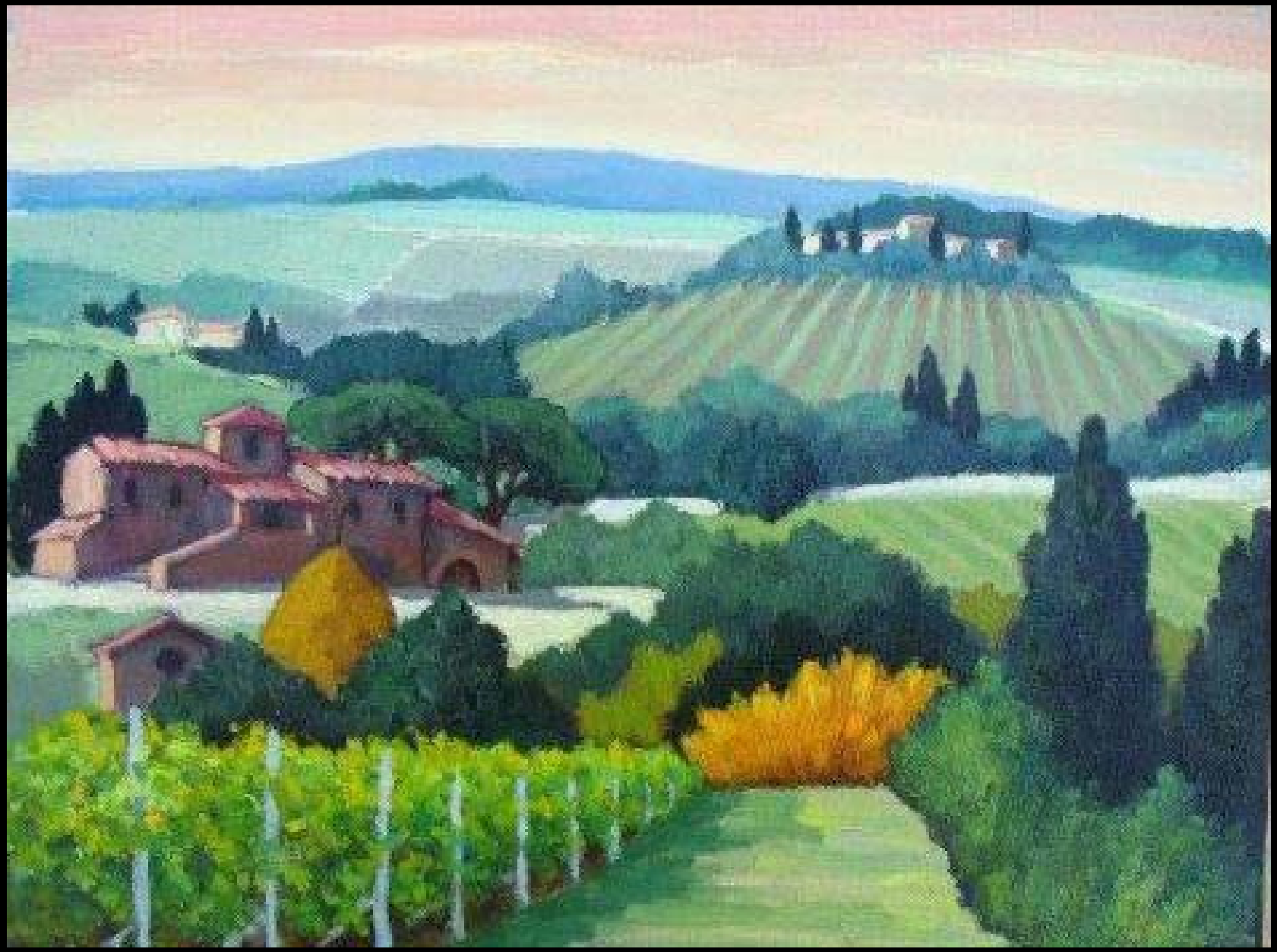
Lewis

Lewis

Lewis

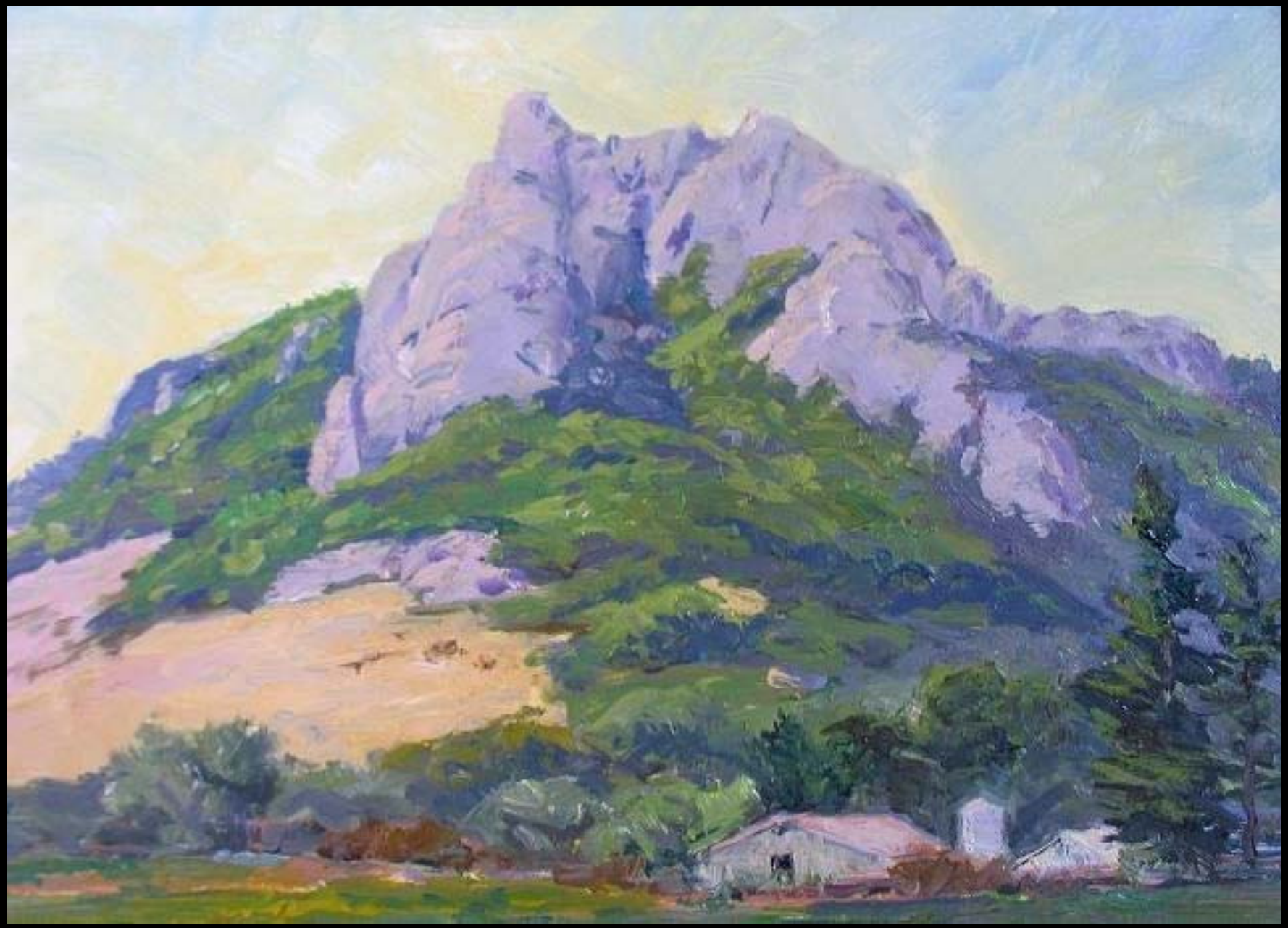
Lewis


M S S M M S S M M S S M
Spaced block



Pessani

Wexler



Schlorff

Stratulat

Hawkins

Mylrea

M S S M M S S M M S S M

Lewis

Lewis

Lewis

Lewis

Lewis

Lewis

Pessani

Wexler

Schlorff

Stratulat

Juras

Mylrea

Juras

Schlorff

Pessani

Mylrea

Wexler

Stratulat

Hawkins

Hawkins

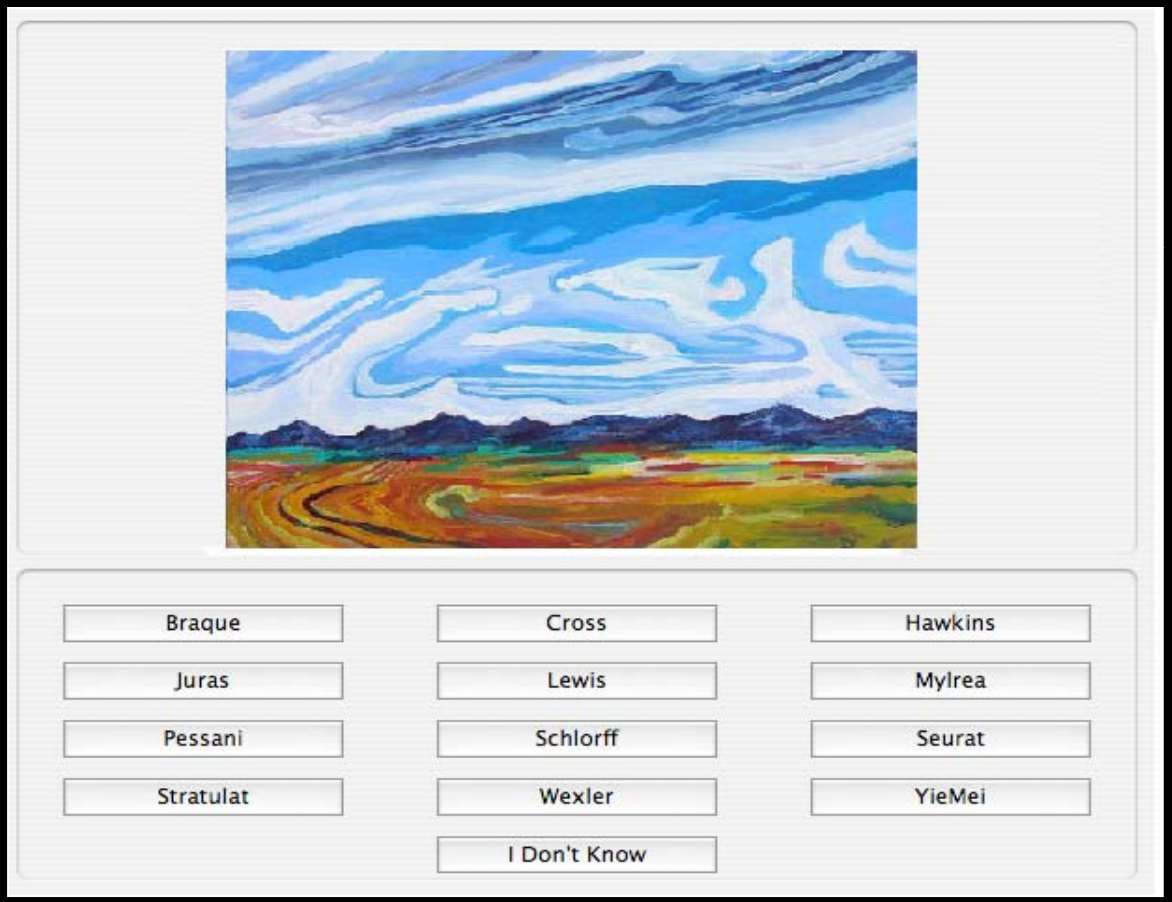
Hawkins

Hawkins

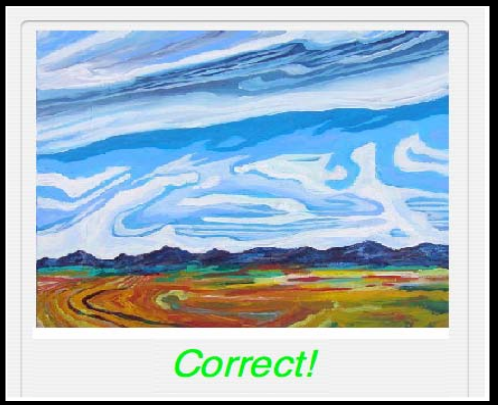
Hawkins

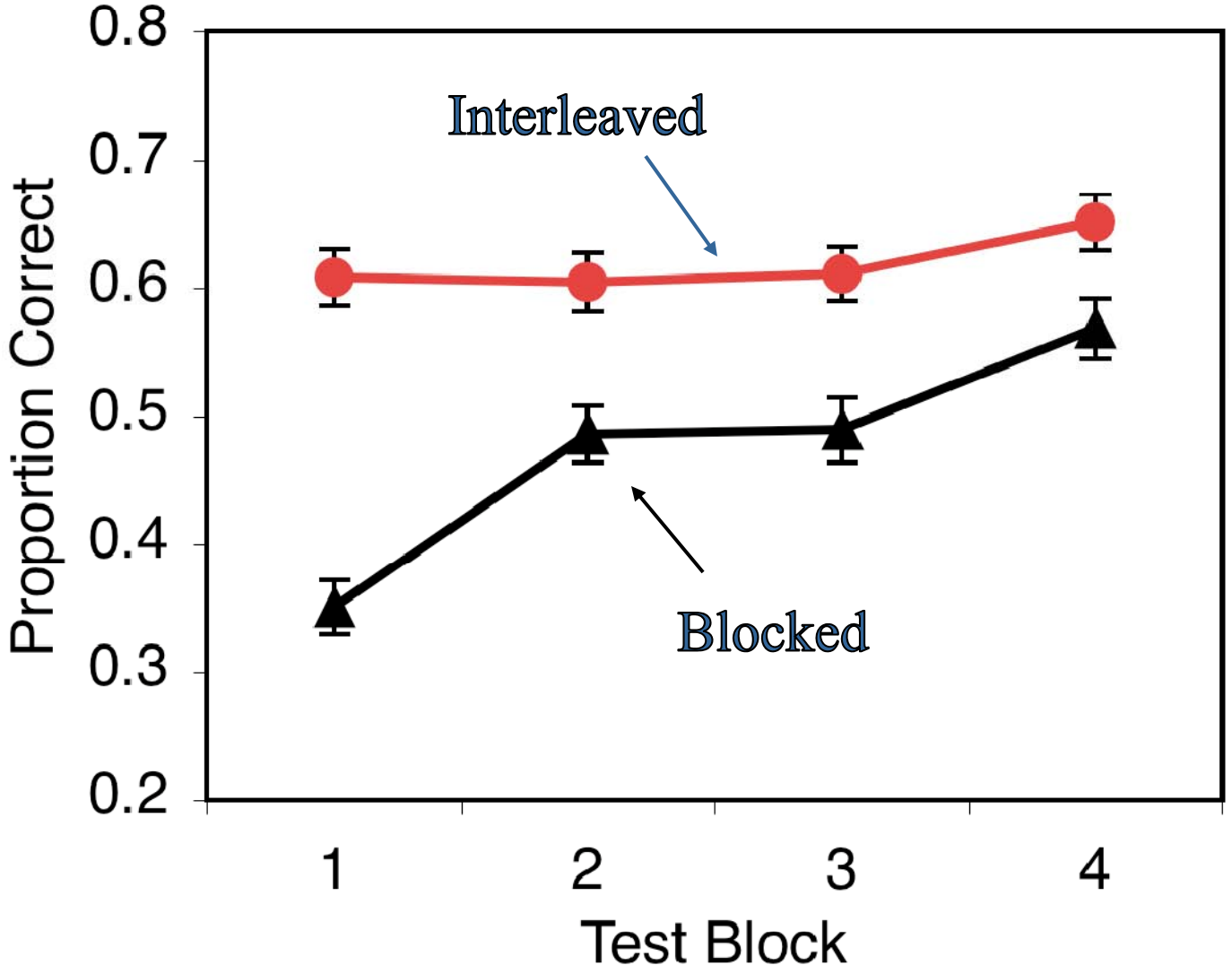
Hawkins

Test



Feedback



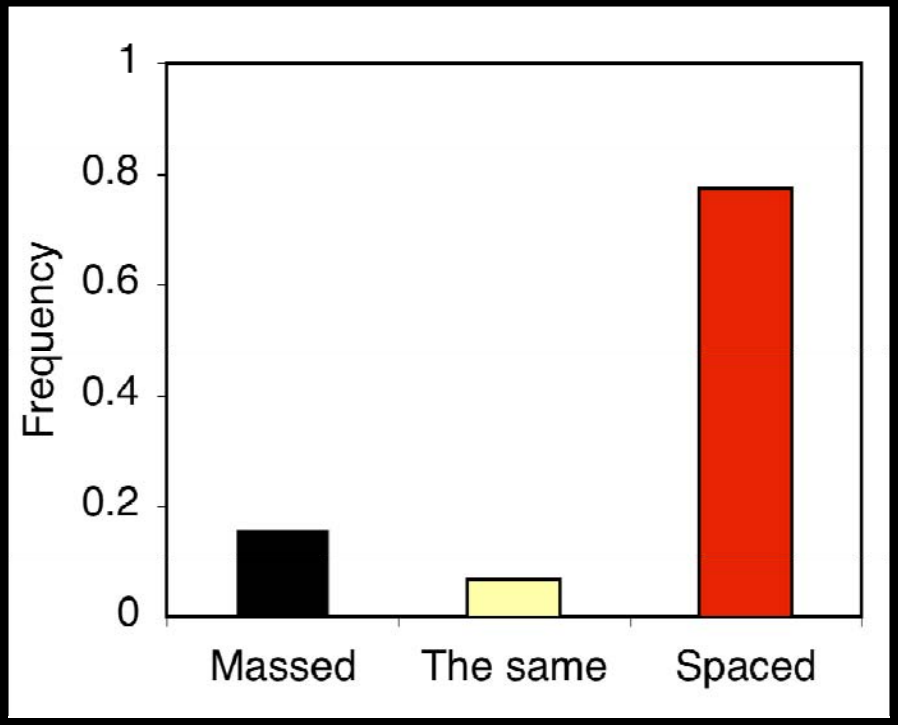

0.8
0.7
0.6
0.5
0.4
0.3
0.2
Proportion Correct
Interleaved
Blocked
1
2
3
4
Test Block

Final Questions

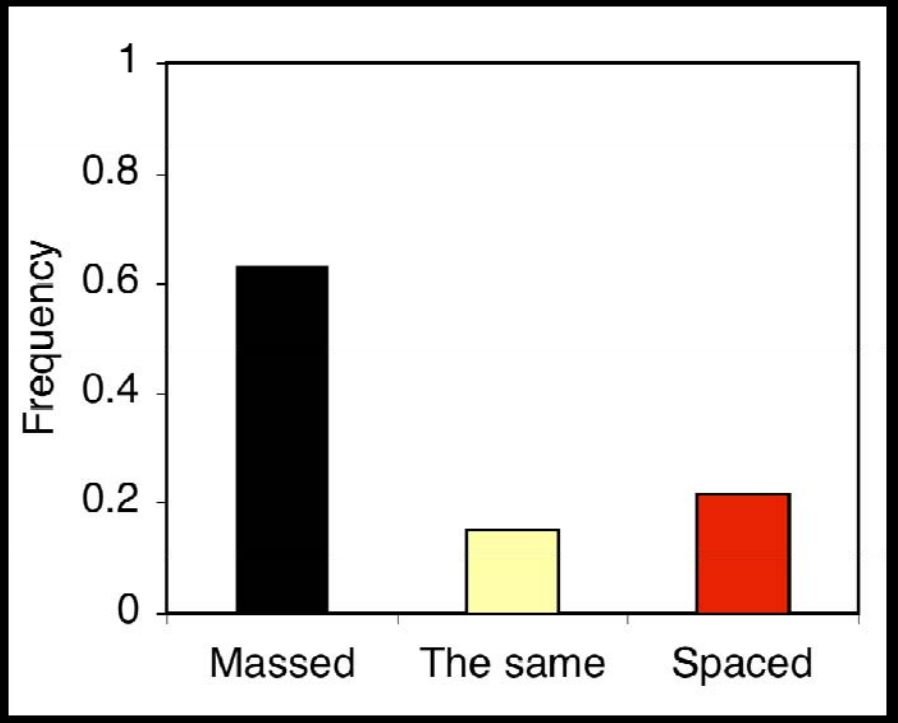
Which do you think helped you learn more, massed or spaced?

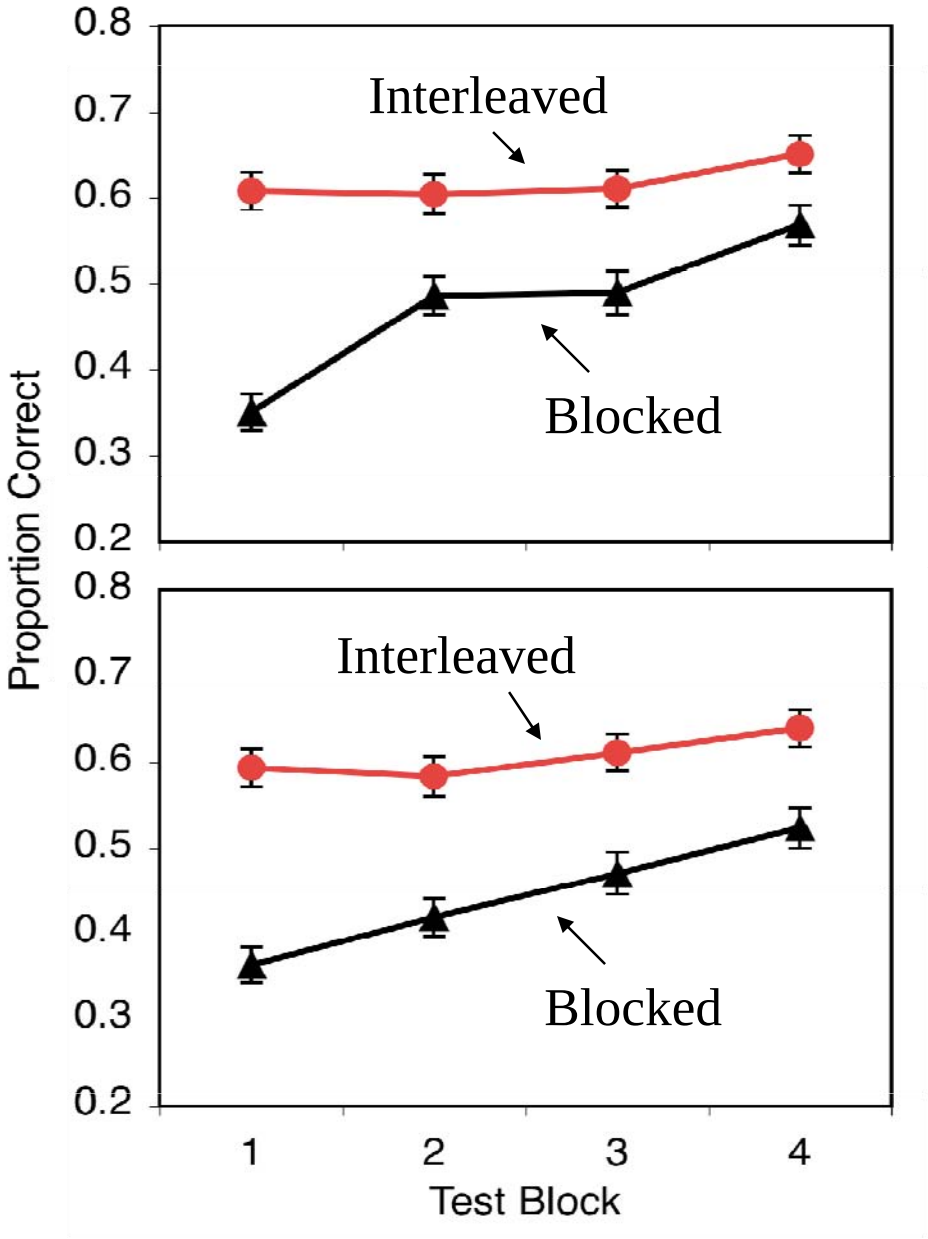
Massed | About the same | Spaced

Actual



Responses





Spacing vs. massing manipulation *within* participants

Spacing vs. massing manipulated *between* participants

Differentiation hypothesis

- Original hypothesis: Blocking/massing highlights similarities


Lewis

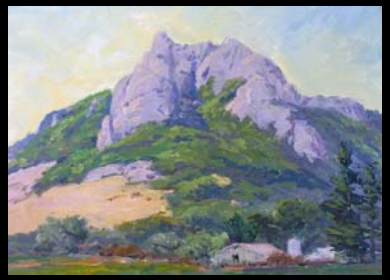

Lewis


Lewis


Lewis

- New hypothesis: Interleaving/spacing highlights differences


Lewis


Schlorff


Hawkins


Lewis

Desirable-difficulties findings: Implications for the design of instruction?

- Variation?
- Interleaving?
- Spacing?
- Using tests/generation as learning events?

Desirable-difficulties findings: Implications for the evaluation of instruction?

- Students' evaluation of teaching?
- Trainees completing "happy" or "smile" sheets in industry?
- Students expectations as to how courses should be taught?

What do college students know and not know about how to study?

- Survey of 431 introductory-psychology students at UCLA
- *The Promise and Perils of Self-regulated Study* (Kornell & Bjork, 2007)

How do you decide what to study next?

59%	Whatever's due soonest/overdue
4%	Whatever I haven't studied for the longest time
4%	Whatever I find interesting
22%	Whatever I feel I'm doing the worst in
11%	I plan my study schedule ahead of time, and I study whatever I've scheduled

Do you usually return to course material to review it after a course has ended?

14% Yes

86% No

When you study, do you typically read a textbook/article/other source material more than once?

16% Yes, I re-read whole chapters/articles

60% Yes, I re-read sections that I underlined or highlighted or marked

23% Not usually

Would you say that you study the way you do because a teacher (or teachers) taught you to study that way?

20% Yes

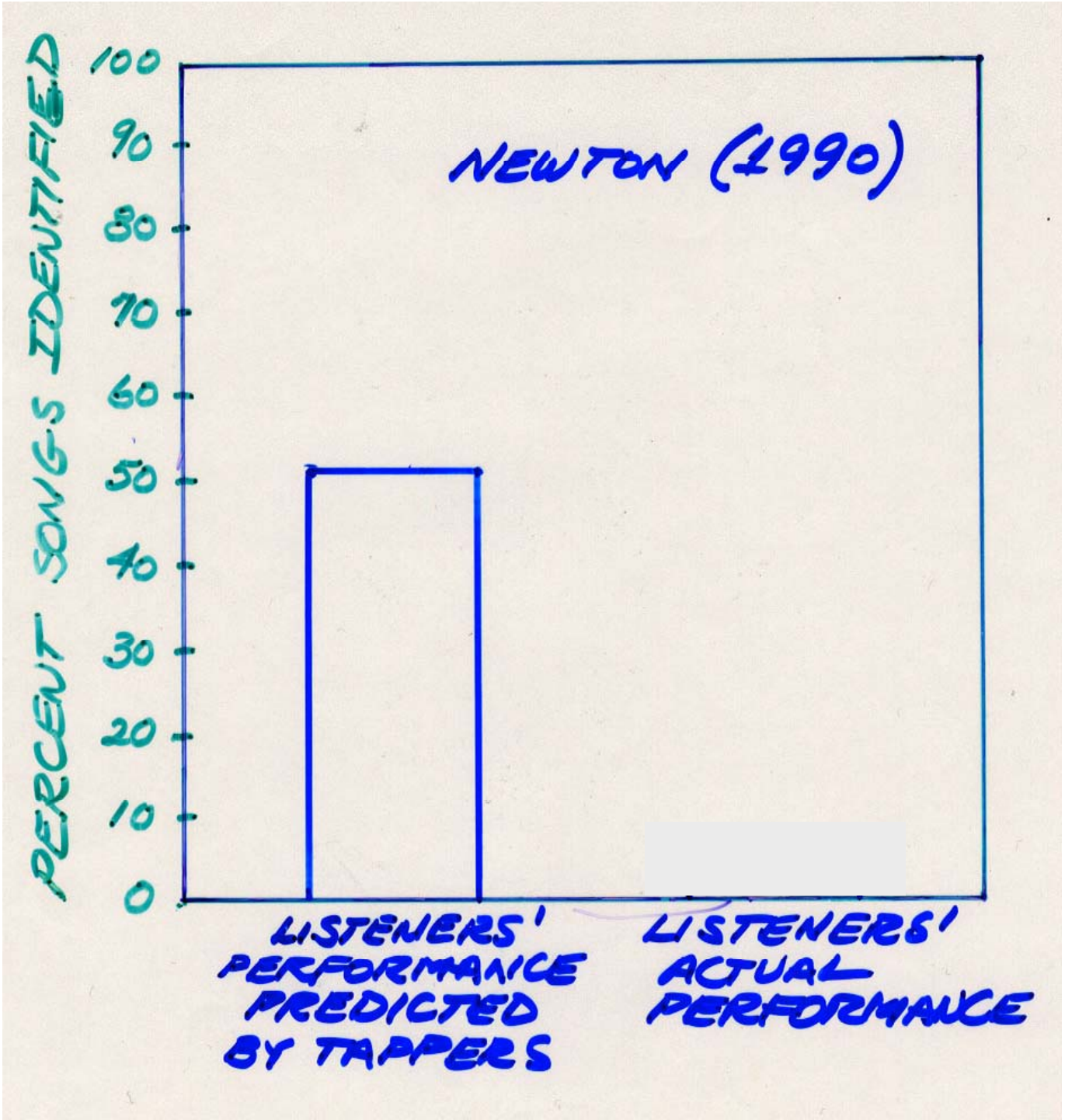
80% No

Enhancing instruction

- If students do not tend to engage in the learning activities that produce durable and flexible learning,
  - the fault is primarily ours;
  - who among us, during our student days, would have answered those survey questions differently?
- We need to structure courses, curricula, requirements, and activities to engage the processes that enhance learning, comprehension, and knowledge integration
  - Doing so requires, among other things, adopting the student's perspective
  - The subjective experience of students versus the subjective experience of teachers

Comments on our subjective experience as teachers

- Egocentrism in social communication
  - Newton (1990) as a parable of teaching;
  - Piaget (1962) quote
  - Calvin & Hobbes


NEWTON (1990)
PERCENT SONGS IDENTIFIED
100
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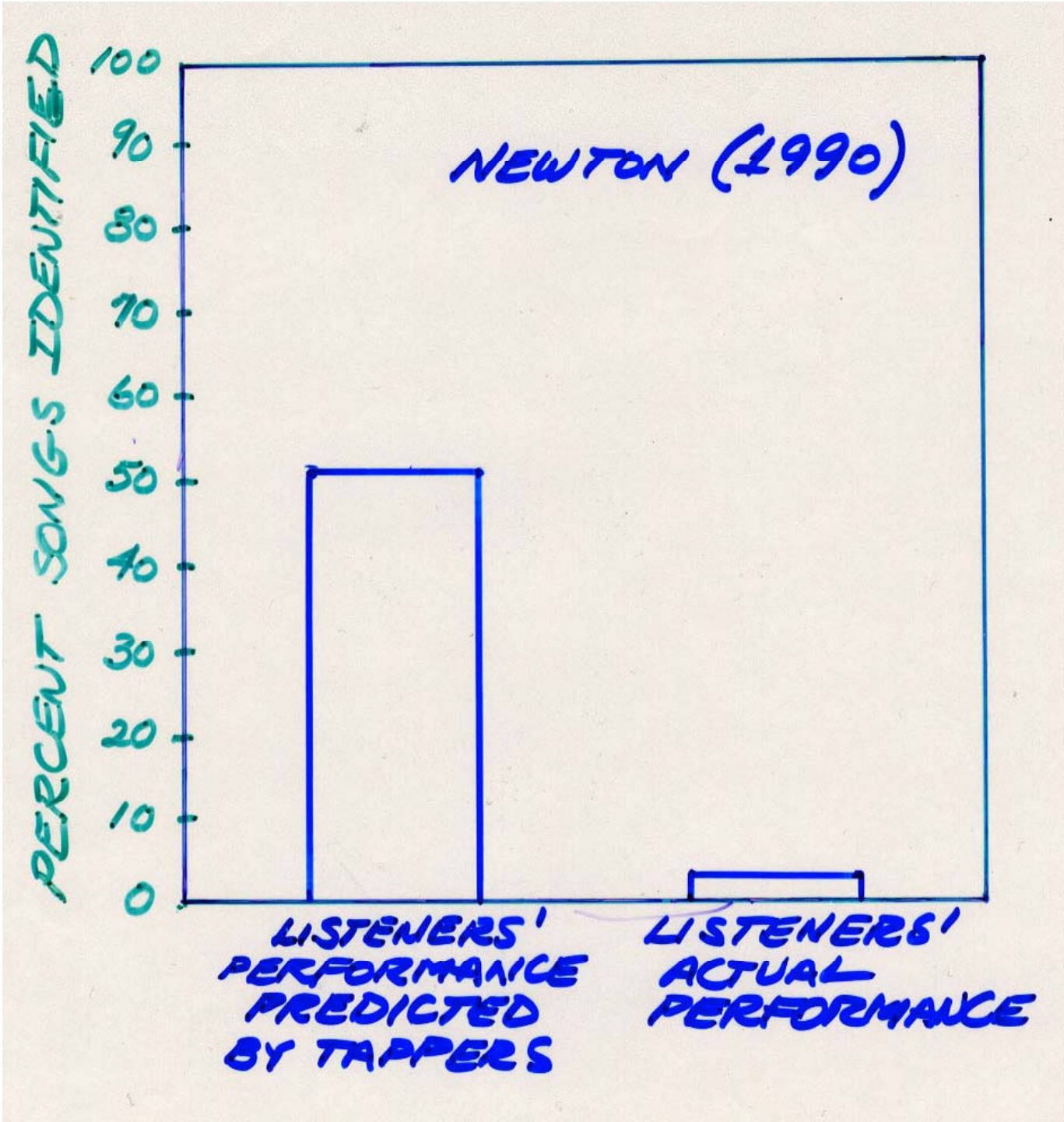
LISTENERS' PERFORMANCE PREDICTED BY TAPPERS
LISTENERS' ACTUAL PERFORMANCE


NEWTON (1990)
PERCENT SONGS IDENTIFIED
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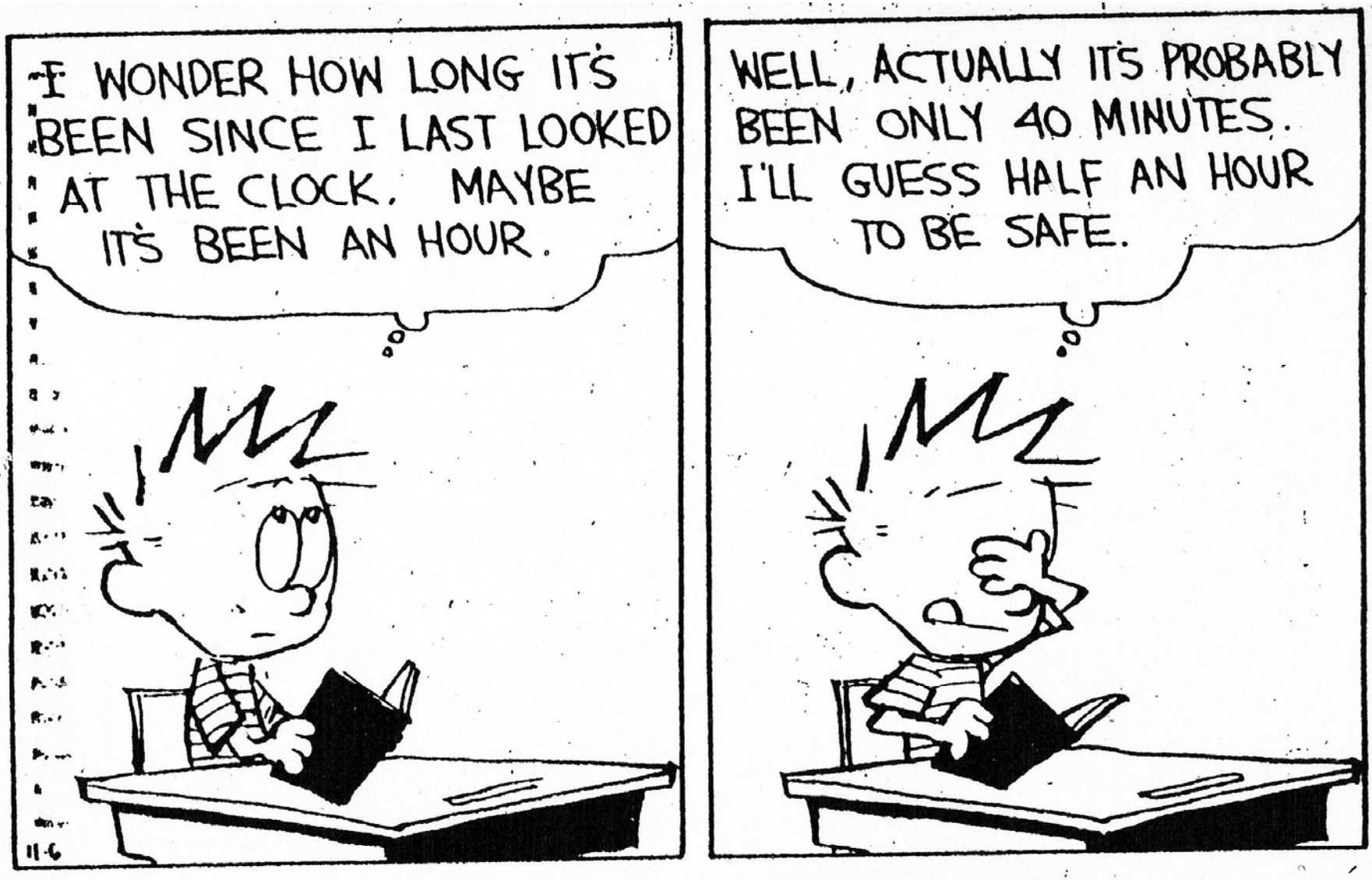
LISTENERS' PERFORMANCE PREDICTED BY TAPPERS
LISTENERS' ACTUAL PERFORMANCE

Piaget (1962)

"Every beginning instructor discovers sooner or later that his first lectures were incomprehensible because he was talking to himself, so to say, mindful only of his point of view. He realizes only gradually and with difficulty that it is not easy to place one's self in the shoes of students who do not yet know about the subject matter of the course."


I WONDER HOW LONG IT'S BEEN SINCE I LAST LOOKED AT THE CLOCK. MAYBE IT'S BEEN AN HOUR.
WELL, ACTUALLY IT'S PROBABLY BEEN ONLY 40 MINUTES. I'LL GUESS HALF AN HOUR TO BE SAFE.


© 1995 Watterson/Dist. by Universal Press Syndicate
20 SECONDS ?!?
IT'S GOING TO BE A VERY BAD DAY.
CALVIN, SIT UP.

- The end…almost

How we learn versus how we think we learn

- Misconceptions
  - We have a faulty mental model of ourselves as learners (human memory versus a videotape recorder)
  - Intuition versus research: We are not, apparently, educated by the trials and errors of everyday living and learning
- Counterproductive attitudes and assumptions
  - Performance indexes learning
  - Efficient learning is easy learning
  - Differences in the performance of individuals reflect differences in innate ability or learning style
    - Individual differences are greatly over-appreciated,
    - The power of experience, practice, and effort is underappreciated
    - Comments on the *styles-of-learning* idea

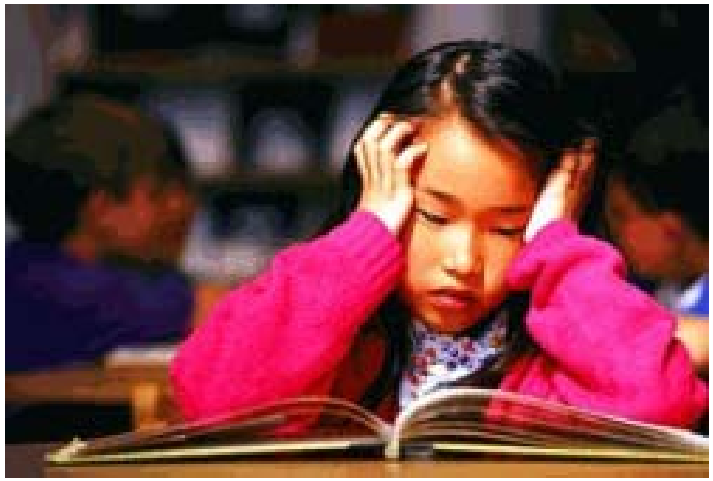
Individual differences and the *styles-of-learning* idea

- *Why is the idea attractive?*
- *Why is it counterproductive?*

Parents Of Nasal Learners Demand Odor-Based Curriculum

March 15, 2000 | Issue 36•09

COLUMBUS, OH–Backed by olfactory-education experts, parents of nasal learners are demanding that U.S. public schools provide odor-based curricula for their academically struggling children.



A nasal learner struggles with an odorless textbook.

"Despite the proliferation of countless scholastic tests intended to identify children with special needs, the challenges facing nasal learners continue to be ignored," said Delia Weber, president of Parents Of Nasal Learners, at the group's annual conference. "Every day, I witness firsthand my son Austin's struggle to succeed in a school environment that recognizes the needs of visual, auditory, tactile, and kinesthetic learners but not him." ... "My child is not stupid," Weber said. "There simply was no way for him to thrive in a school that only caters to traditional students who absorb educational concepts by hearing, reading, seeing, discussing, drawing, building, or acting out."

Pashler, H. McDaniel, M., Rohrer, D., & Bjork, R. A. (in press). Learning styles: A review of concepts and evidence. *Psychological Science in the Public Interest.*

Individual difference *do* matter, and matter greatly

- New learning builds on--and depends on--old learning
- Personal, family, and cultural histories affect, among other things
  - Motivation to learn;
  - The degree to which learning is valued;
  - Aspirations and expectations with respect to learning;
  - The knowledge and assumptions brought to new learning
- Example: Lee and Bjork (2004)

Which Order Is Optimal?

Doing the Readings

Then

Attending Lecture

OR

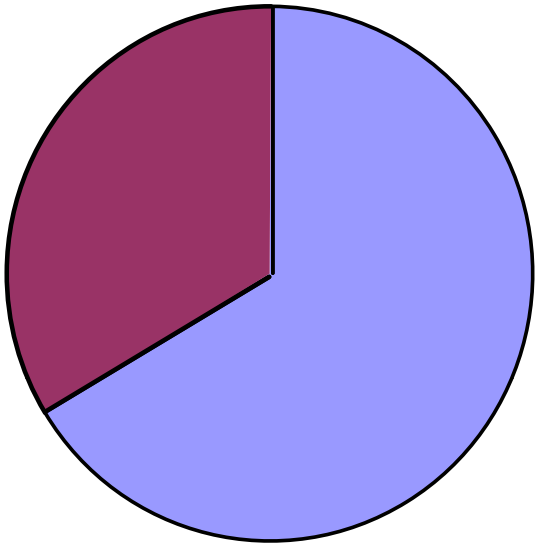
Attending Lecture

Then

Doing the Readings

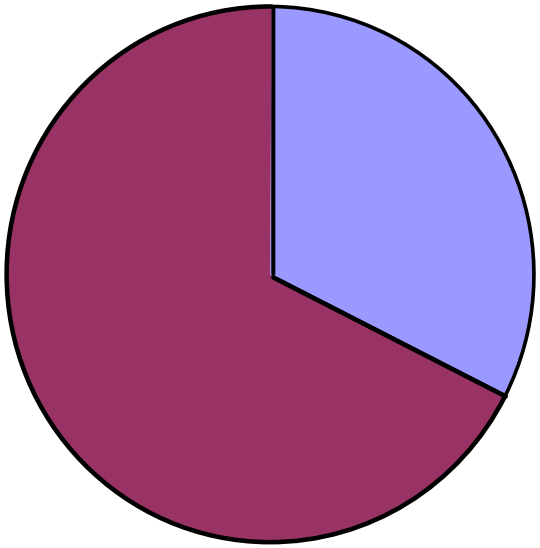
What Do You Do?

34% 66%



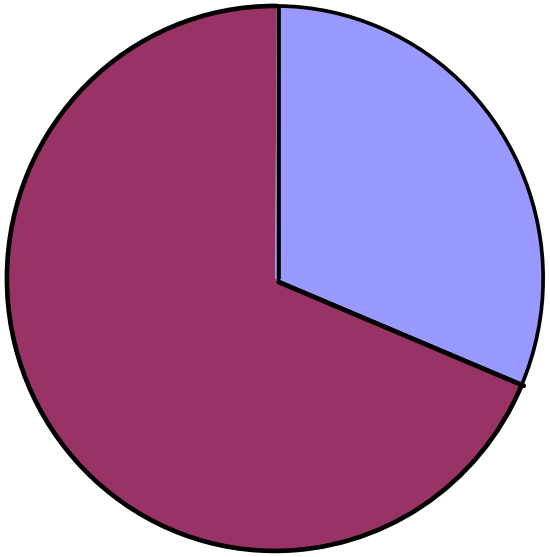
Which Is More Effective?

67% 33%



Which Is More Difficult?

66% 34%



Text then Lecture

Lecture then Text

The bottom line …

- We *all*, barring an organic disorder, have an incredible capacity to learn

- The actual end

References

- Baddeley, A.D., & Longman, D.J.A. (1978). The influence of length and frequency of training session on the rate of learning to type. *Ergonomics, 21,* 627-635.
- Benjamin, A. S., Bjork, R. A., & Schwartz, B. L. (1998). The mismeasure of memory: When retrieval fluency is misleading as a metamnemonic index. *Journal of Experimental Psychology: General, 127,* 55-68.
- Bjork, R.A. (1994). Memory and metamemory considerations in the training of human beings. In J. Metcalfe and A. Shimamura (Eds.), *Metacognition: Knowing about knowing.* (pp.185-205). Cambridge, MA: MIT Press.
- Bjork, R. A., & Bjork, E. L. (1992). A new theory of disuse and an old theory of stimulus fluctuation. In A. Healy, S. Kosslyn, & R. Shiffrin (Eds.), *From learning processes to cognitive processes: Essays in honor of William K. Estes* (Vol. 2, pp. 35-67). Hillsdale, NJ: Erlbaum.
- Estes, W.K. (1955). Statistical theory of distributional phenomena in learning. *Psychological Review, 62,* 369-377.
- Hull, C. L. (1943). *The principles of behavior*. New York: Appleton-Century-Crofts.
- Jacoby, L. L., Bjork, R. A., & Kelley, C. M. (1994). Illusions of comprehension, competence, and remembering. In D. Druckman and R. A. Bjork (Eds.), *Learning, remembering, believing: Enhancing human performance* (pp.57-80). Washington, DC: National Academy Press.
- Karpicke, J.D., & Roediger, H.L. (2008). The critical importance of retrieval for learning. *Science, 319, 966-968.*
- Kerr, R., & Booth, B. (1978). Specific and varied practice of a motor skill. *Perceptual and Motor Skills, 46,* 395-401.

References (continued)

- Kornell, N., & Bjork, R. A. (2007). The promise and perils of self-regulated study. *Psychonomic Bulletin & Review, 14*, 219–224.
- Kornell, N., & Bjork, R. A. (2008). Learning concepts and categories: Is spacing the "enemy of induction"? *Psychological Science, 19*, 585-592.
- Kornell, N., Hays, M. J., & Bjork, R. A. (2009). Unsuccessful retrieval attempts enhance subsequent learning. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 35(4),* 2009, 989-998.
- Mannes S. M., & Kintsch, W. (1987). Knowledge organization and text organization. *Cognition and Instruction, 4,* 91-115.
- Newton, L. (1990). *Overconfidence in the Communication of Intent: Heard and Unheard Melodies.* Unpublished doctoral dissertation, Department of Psychology, Stanford University.
- Pashler, H. McDaniel, M., Rohrer, D., & Bjork, R. A. (in press). Learning styles: A review of concepts and evidence. *Psychological Science in the Public Interest.*
- Piaget, J. (1962). *Play, Dreams and Imitation in Childhood*. New York: Norton.
- Reder, L. M. (1987). Selection strategies in question answering. *Cognitive Psychology, 19*, 90-138.
- Roediger, H.L. & Karpicke, J.D. (2006). Test-enhanced learning: Taking memory tests improves long-term retention. *Psychological Science, 17*, 249-255.
- Rohrer, D., & Taylor, K. (2007). The shuffling of mathematics practice problems improves learning. *Instructional Science, 35, 481-498.*

References (continued)

- Simon, D. A., & Bjork, R. A. (2001). Metacognition in motor learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 27,* 907-912.
- Smith, S. M, Glenberg, A. M., & Bjork, R. A. (1978). Environmental context and human memory. *Memory & Cognition, 6,* 342-353.
- Smith, M. K., Wood, W. B., Adams, W. K., Wieman, C., Knight, J. K., Guild, N., & Su, T. T. (2009). Why peer discussion improves student performance on in-class concept questions. *Science, 323,* 122-124.
- Ste-Marie, D. M., Clark, S. E., Findlay, L. C. & Latimer A. E. (2004). High levels of contextual interference enhance handwriting skill acquisition. *Journal of Motor Behavior, 36,* 115-126.