CS 544
Experimental Design

What is experimental design?
What is an experimental hypothesis?
How do I plan an experiment?
Why are statistics used?
What are the important statistical methods?

Acknowledgement: Some of the material in this lecture is based on material prepared for similar courses by Saul Greenberg (University of Calgary)

Quantitative ways to evaluate systems

- Quantitative:
  - precise measurement, numerical values
  - bounds on how correct our statements are
- Methods
  - Controlled Experiments
  - Statistical Analysis
- Measures
  - Objective: user performance (speed & accuracy)
  - Subjective: user satisfaction

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Quantitative methods

1. User performance data collection
   - data is collected on system use

descriptive statistics:

- frequency of request for on-line
  - what did people ask for help with?
- frequency of use of different parts of the system
  - why are parts of system unused?
- number of errors and where they occurred
  - why does an error occur repeatedly?
- time it takes to complete some operation
  - what tasks take longer than expected?

   - collect heaps of data in the hope that something interesting shows up
   - often difficult to sift through data unless specific aspects are targeted (as in list above)

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Quantitative methods ...

2. Controlled experiments

The traditional scientific method

- reductionist
  - clear convincing result on specific issues
- In HCI:
  - insights into cognitive process, human performance limitations, ...
  - allows comparison of systems, fine-tuning of details ...

Strives for

- lucid and testable hypothesis (usually a causal inference)
- quantitative measurement
- measure of confidence in results obtained (inferencial statistics)
- replicability of experiment
- control of variables and conditions
- removal of experimenter bias

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The experimental method

a) Begin with a lucid, testable hypothesis

- Example 1:

H_0: there is no difference in the number of cavities in children and teenagers using crest and no-teeth toothpaste

H_1: children and teenagers using crest toothpaste have fewer cavities than those who use no-teeth toothpaste

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The experimental method

a) Begin with a lucid, testable hypothesis

- Example 2:

H_0: there is no difference in user performance (time and error rate) when selecting a single item from a pop-up or a pull down menu, regardless of the subject's previous expertise in using a mouse or using the different menu types

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The experimental method

b) Explicitly state the independent variables that are to be altered

Independent variables

- the things you control (independent of how a subject behaves)
- two different kinds:
  1. treatment manipulated (can establish cause/effect, true experiment)
  2. subject individual differences (can never fully establish cause/effect)

in toothpaste experiment

- toothpaste type: uses Crest or No-teeth toothpaste
- age: <= 12 years *or* > 12 years

in menu experiment

- menu type: pop-up or pull-down
- menu length: 3, 6, 9, 12, 15
- expertise: expert or novice

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The experimental method

c) Carefully choose the dependent variables that will be measured

Dependent variables

- variables dependent on the subject's behaviour / reaction to the independent variable

in toothpaste experiment

- number of cavities
- frequency of brushing

in menu experiment

- time to select an item
- selection errors made

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The experimental method

d) Judiciously select and assign subjects to groups

Ways of controlling subject variability

- recognize classes and make them and independent variable
- minimize unaccounted anomalies in subject group
  - superstars versus poor performers
- use reasonable number of subjects and random assignment

Novice

Expert

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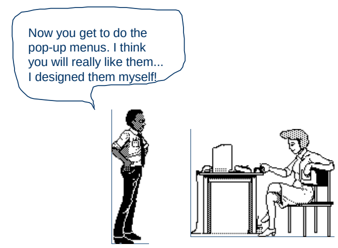
The experimental method...

e) Control for biasing factors

- unbiased instructions + experimental protocols
  - prepare ahead of time
- double-blind experiments, ...



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The experimental method

f) Apply statistical methods to data analysis

- Confidence limits: the confidence that your conclusion is correct
  - “The hypothesis that mouse experience makes no difference is rejected at the .05 level” (i.e., null hypothesis rejected)
  - means:
    - a 95% chance that your finding is correct
    - a 5% chance you are wrong

g) Interpret your results

- what *you* believe the results mean, and their implications
- yes, there can be a subjective component to quantitative analysis

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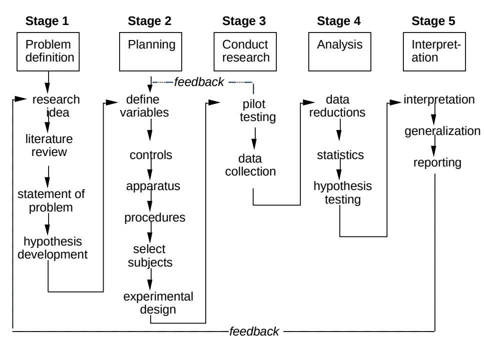
The Planning Flowchart



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Statistical Analysis

- What is a statistic?
  - a number that describes a sample
  - sample is a subset (hopefully representative) of the population we are interested in understanding
- Statistics are calculations that tell us
  - mathematical attributes about our data sets (sample)
    - mean, amount of variance, ...
  - how data sets relate to each other
    - whether we are “sampling” from the same or different populations
  - the probability that our claims are correct
    - “statistical significance”

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Example: Differences between means

- Given: two data sets measuring a condition
  - eg height difference of males and females,
    time to select an item from different menu styles
    ...
- Question:
  - is the difference between the means of the data statistically significant?
- Null hypothesis:
  - there is no difference between the two means
  - statistical analysis can only reject the hypothesis at a certain level of confidence
  - we never actually prove the hypothesis true

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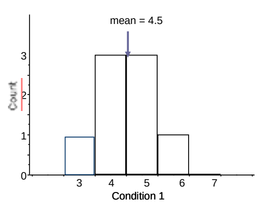
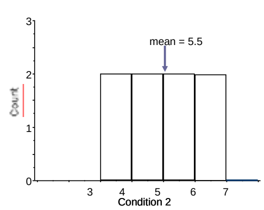
Example:

Is there a *significant* difference between the means?

Condition one: 3, 4, 4, 4, 5, 5, 5, 6



Condition two: 4, 4, 5, 5, 6, 6, 7, 7



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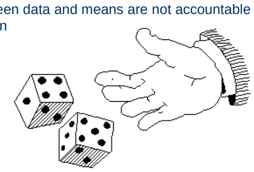
The problem with visual inspection of data

- There is almost always variation in the collected data
- Differences between data sets may be due to:
  - normal variation
    - eg two sets of ten tosses with different but fair dice
      - differences between data and means are accountable by expected variation
  - real differences between data
    - eg two sets of ten tosses with loaded dice and fair dice
      - differences between data and means are not accountable by expected variation



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T-test

A statistical test

Allows one to say something about differences between means at a certain confidence level

Null hypothesis of the T-test:
- no difference exists between the means

Possible results:
- I am 95% sure that null hypothesis is rejected
  - there is probably a true difference between the means
- I cannot reject the null hypothesis
  - the means are likely the same

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Different types of T-tests

Comparing two sets of independent observations
- usually different subjects in each group (number may differ as well)

Condition 1	Condition 2
S1–S20	S21–43

Paired observations
- usually single group studied under separate experimental conditions
- data points of one subject are treated as a pair

Condition 1	Condition 2
S1–S20	S1–S20

Non-directional vs directional alternatives
- non-directional (two-tailed)
  - no expectation that the direction of difference matters
- directional (one-tailed)
  - Only interested if the mean of a given condition is greater than the other

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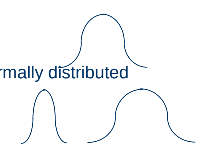
T-tests

- Assumptions of t-tests
  - data points of each sample are normally distributed
    - but t-test very robust in practice
  - sample variances are equal
    - t-test reasonably robust for differing variances
    - deserves consideration
  - individual observations of data points in sample are independent
    - must be adhered to
- Significance level
  - decide upon the level before you do the test!
  - typically stated at the .05 or .01 level



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Two-tailed unpaired T-test

- n: number of data points in the one sample ($N = n_1 + n_2$)
- ΣX: sum of all data points in one sample
- $\overline{X}$: mean of data points in sample
- $\Sigma(X^2)$: sum of squares of data points in sample
- s^2: unbiased estimate of population variation
- t: t ratio
- df = degrees of freedom = N1 + N2 – 2
- Formulas

$$s^2 = \frac{\Sigma(X_1^2) - \frac{(\Sigma X_1)^2}{n_1} + \Sigma(X_2^2) - \frac{(\Sigma X_2)^2}{n_2}}{n_1 + n_2 - 2}$$

$$t = \frac{\overline{X}_1 - \overline{X}_2}{\sqrt{\frac{s^2}{n_1} + \frac{s^2}{n_2}}}$$

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Level of significance for two-tailed test

df	*.05*	*.01*
1	12.706	63.657
2	4.303	9.925
3	3.182	5.841
4	2.776	4.604
5	2.571	4.032
6	2.447	3.707
7	2.365	3.499
8	2.306	3.355
9	2.262	3.250
10	2.228	3.169
11	2.201	3.106
12	2.179	3.055
13	2.160	3.012
14	2.145	2.977
15	2.131	2.947

df	*.05*	*.01*
16	2.120	2.921
18	2.101	2.878
20	2.086	2.845
22	2.074	2.819
24	2.064	2.797

Critical value (threshold) that t statistic much reach to achieve significance.

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Example Calculation

x_1 = 3 4 4 4 5 5 5 6
x_2 = 4 4 5 5 6 6 7 7

Hypothesis: there is no significant difference between the means at the .05 level

Step 1. Calculating s^2

	1	2
N	8	8
Σx	36	44
$\bar{x}$	4.5	5.5
$\Sigma(x^2)$	168	252
$(\Sigma x)^2$	1296	1936

$df = 14$

$$s^2 = \frac{\Sigma x_1^2 - (\Sigma x_1)^2/N_1 + \Sigma x_2^2 - (\Sigma x_2)^2/N_2}{N_1 + N_2 - 2}$$

$$= \frac{168 - 1296/8 + 252 - 1936/8}{8+8-2}$$

$$= 1.1429$$

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Example Calculation

Step 2. Calculating *t*

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{s^2/N_1 + s^2/N_2}}$$

$$= \frac{4.5 - 5.5}{\sqrt{2 \cdot (1.1429/8)}}$$

$$= \frac{-1}{.5345}$$

$$= -1.871$$

Step 3: Looking up critical value of *t*
- Use table for two-tailed *t*-test, at *p*=.05, *df*=14
- critical value = 2.145
- because *t*=1.871 < 2.145, there is no significant difference
- therefore, we cannot reject the null hypothesis
  i.e., there is no difference between the means

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Two-tailed Unpaired T-test

Condition one: 3, 4, 4, 4, 5, 5, 5, 6

Condition two: 4, 4, 5, 5, 6, 6, 7, 7

What the results would look like in stats software.

Unpaired t-test

DF:	Unpaired t Value:	Prob. (2-tail):
14	-1.871	.0824

Group:	Count:	Mean:	Std. Dev.:	Std. Error:
one	8	4.5	.926	.327
two	8	5.5	1.195	.423

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Choice of significance levels and two types of errors

- Type I error: reject the null hypothesis when it is, in fact, true (α = .05)
- Type II error: accept the null hypothesis when it is, in fact, false (β)

	H_0 True	H_0 False
Reject H_0	α (Type I error)	1 - β (Power)
Not Reject H_0	1 - α	β (Type II error)

- Effects of levels of significance
  - very high confidence level (eg .0001) gives greater chance of Type II errors
  - very low confidence level (eg .1) gives greater chance of Type I errors
  - tradeoff: choice often depends on effects of result

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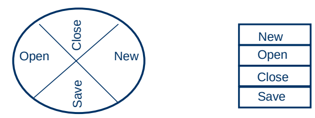
Choice of significance levels and two types of errors

H_0 There is no difference between Pie menus and traditional pop-up menus



- Type I: (reject H_0, believe there is a difference, when there isn't)
  - extra work developing software and having people learn a new idiom for no benefit
- Type II: (accept H_0, believe there is no difference, when there is)
  - use a less efficient (but already familiar) menu

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Choice of significance levels and two types of errors

- Type I: (reject H_0, believe there is a difference, when there isn't)
  - extra work developing software and having people learn a new idiom for no benefit
- Type II: (accept H_0, believe there is no difference, when there is)
  - use a less efficient (but already familiar) menu
- Case 1: Redesigning a traditional GUI interface
  - a Type II error is preferable to a Type I error , Why?
- Case 2: Designing a digital mapping application where experts perform extremely frequent menu selections
  - a Type I error is preferable to a Type II error, Why?

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Other Tests: Correlation

- Measures the extent to which two concepts are related
  - eg years of university training vs computer ownership per capita
- How?
  - obtain the two sets of measurements
  - calculate correlation coefficient
    - +1: positively correlated
    - 0: no correlation (no relation)
    - –1: negatively correlated
- Dangers
  - attributing causality
    - a correlation does not imply cause and effect
    - cause may be due to a third “hidden” variable related to both other variables
    - eg (above example) age, affluence
  - drawing strong conclusion from small numbers
    - unreliable with small groups
    - be wary of accepting anything more than the direction of correlation unless you have at least 40 subjects

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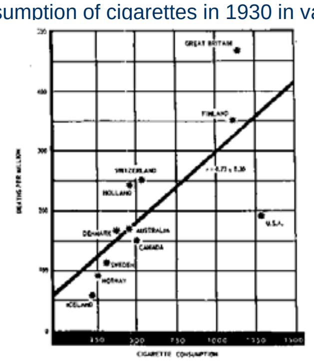
Sample Study: Cigarette Consumption

Crude Male death rate for lung cancer in 1950 per capita consumption of cigarettes in 1930 in various countries.



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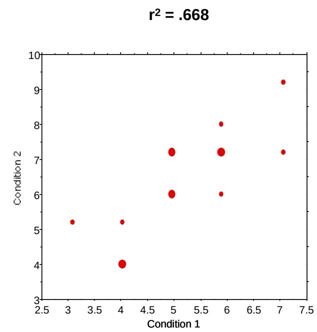
Correlation

condition 1	condition 2
5	6
4	5
6	7
4	4
5	6
3	5
5	7
4	4
5	7
6	7
6	6
7	7
6	8
7	9



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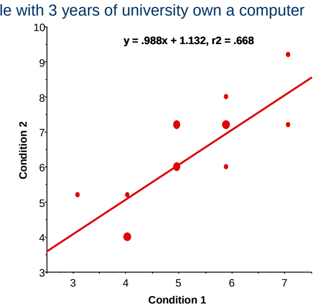
Regression

- Calculate a line of “best fit”
- use the value of one variable to predict the value of the other
  - e.g., 60% of people with 3 years of university own a computer

condition 1	condition 2
5	6
4	5
6	7
4	4
5	6
3	5
5	7
4	4
5	7
6	7
6	6
7	7
6	8
7	9



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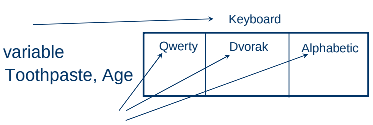
Analysis of Variance (Anova)

- A Workhorse
  - allows moderately complex experimental designs and statistics
- Terminology
  - Factor
    - independent variable
    - ie Keyboard, Toothpaste, Age
  - Factor level
    - specific value of independent variable
    - ie Qwerty, Crest, 5-10 years old



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Anova terminology

- Between subjects
  - a subject is assigned to only one factor level of treatment
  - problem: greater variability, requires more subjects

Keyboard

Qwerty	Dvorak	Alphabetic
S1-20	*S21-40*	*S41-60*

- Within subjects
  - subjects assigned to all factor levels of a treatment
  - requires fewer subjects
  - less variability as subject measures are paired
  - problem: order effects (eg learning)
  - partially solved by counter-balanced ordering

Keyboard

Qwerty	Dvorak	Alphabetic
S1-20	*S1-20*	*S1-20*

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F statistic

- Within group variability (WG)
  - individual differences
  - measurement error

Keyboard

Qwerty	Dvorak	Alphabetic
5, 9, 7, 6, … 3, 7	3, 9, 11, 2, … 3, 10	3, 5, 5, 4, … 2, 5

- Between group variability (BG)
  - treatment effects
  - individual differences
  - measurement error

Keyboard

Qwerty	Dvorak	Alphabetic
5, 9, 7, 6, … 3, 7	3, 9, 11, 2, … 3, 10	3, 5, 5, 4, … 2, 5

- These two variabilities are independent of one another
- They combine to give total variability
- We are mostly interested in between group variability because we are trying to understand the effect of the treatment

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F Statistic

$$F = \frac{BG}{WG} = \frac{\text{treatment + id + m.error}}{\text{id + m.error}} = 1.0$$

If there are treatment effects then the numerator becomes inflated

Within-subjects design: the id component in numerator and denominator factored out, therefore a more powerful design

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F statistic

- Similar to the t-test, we look up the F value in a table, for a given α and degrees of freedom to determine significance
- Thus, F statistic sensitive to sample size.
  - Big N → Big Power → Easier to find significance
  - Small N → Small Power → Difficult to find significance
- What we (should) want to know is the effect size
  - Does the treatment make a big difference (i.e., large effect)?
  - Or does it only make a small difference (i.e., small effect)?
  - Depending on what we are doing, small effects may be important findings

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Statistical significance vs Practical significance

- when *N* is large, even a trivial difference (small effect) may be large enough to produce a statistically significant result
  - eg menu choice:
    mean selection time of menu A is 3 seconds;
    menu B is 3.05 seconds
- Statistical significance does not imply that the difference is important!
  - a matter of interpretation, i.e., subjective opinion
  - should always report means to help others make their opinion
- There are measures for effect size, regrettably they are not widely used in HCI research

Single Factor Analysis of Variance

- Compare means between two or more factor levels within a single factor
- example:
  - dependent variable: typing speed
  - independent variable (factor): keyboard
  - between subject design

Qwerty	Alphabetic	Dvorak
S1: 25 secs S2: 29 ... S20: 33	S21: 40 secs S22: 55 ... S40: 33	S51: 17 secs S52: 45 ... S60: 23

Anova terminology

- Factorial design
  - cross combination of levels of one factor with levels of another
  - eg keyboard type (3) x expertise (2)
- Cell
  - unique treatment combination
  - eg qwerty x non-typist

expertise		Keyboard: Qwerty	Dvorak	Alphabetic
	non-typist			
	typist			

Anova terminology

- Mixed factor
  - contains both between and within subject combinations

expertise		Keyboard: Qwerty	Dvorak	Alphabetic
	non-typist	*S1-20*	*S1-20*	*S1-20*
	typist	*S21-40*	*S21-40*	*S21-40*

Anova

- Compares the relationships between many factors
- Provides more informed results
  - considers the interactions between factors
  - eg
    - typists type faster on Qwerty, than on alphabetic and Dvorak
    - there is no difference in typing speeds for non-typists across all keyboards

	Qwerty	Alphabetic	Dvorak
non-typist	S1-S10	S11-S20	S21-S30
typist	S31-S40	S41-S50	S51-S60

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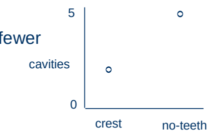
Anova

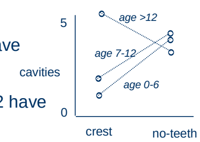
- In reality, we can rarely look at one variable at a time
- Example:
  - t-test:
    Subjects who use crest have fewer cavities



  - anova: toothpaste x age

    Subjects who are 12 or less have fewer cavities with crest.

    Subjects who are older than 12 have fewer cavities with no-teeth.



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Anova case study

- The situation
  - text-based menu display for very large telephone directory
  - names are presented as a range within a selectable menu item
  - users navigate until unique names are reached

1) Arbor	- Kalmer
2) Kalmerson	- Ulston
3) Unger	- Zlotsky

1) Arbor	- Farquar
2) Farston	- Hoover
3) Hover	- Kalmer

...

1) Horace	- Horton
2) Hoover, James	
3) Howard, Rex	

  - but several ways are possible to display these ranges

- Question
  - what display method is best?

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Range Delimeters →

Truncation ↓

1) Arbor	- Barney
2) Barrymore	- Dacker
3) Danby	- Estovitch
4) Farquar	- Kalmer
5) Kalmerson	- Moreen
6) Moriarty	- Praleen
7) Proctor	- Sageen
8) Sagin	- Ulston
9) Unger	- Zlotsky

1) Arbor
2) Barrymore
3) Danby
4) Farquar
5) Kalmerson
6) Moriarty
7) Proctor
8) Sagin
9) Unger
--(Zlotsky)

-- (Arbor)
1) Barney
2) Dacker
3) Estovitch
4) Kalmer
5) Moreen
6) Praleen
7) Sageen
8) Ulston
9) Zlotsky

1) A	- Barn
2) Barr	- Dac
3) Dan	- E
4) F	- Kalmerr
5) Kalmers	- More
6) Mori	- Pra
7) Pro	- Sage
8) Sagi	- Ul
9) Un	- Z

1) A
2) Barr
3) Dan
4) F
5) Kalmers
6) Mori
7) Pro
8) Sagi
9) Un
--(Z)

-- (A)
1) Barn
2) Dac
3) E
4) Kalmera
5) More
6) Pra
7) Sage
8) Ul
9) Z

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Span

as one descends the menu hierarchy, name suffixes become similar

Wide Span	*Narrow Span*
1) Arbor	1) Danby
2) Barrymore	2) Danton
3) Danby	3) Desiran
4) Farquar	4) Desis
5) Kalmerson	5) Dolton
6) Moriarty	6) Dormer
7) Proctor	7) Eason
8) Sagin	8) Erick
9) Unger	9) Fabian
--(Zlotsky)	--(Farquar)

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Anova case study

Null hypothesis

- six menu display systems based on combinations of *truncation* and *delimiter* methods do not differ significantly from each other as measured by people's scanning speed and error rate
- *menu span* and *user experience* has no significant effect on these results

- 2 level (truncation) x
  2 level (menu span) x
  2 level (experience) x
  3 level (delimiter)
- mixed design

		Truncated		Not Truncated	
		narrow	wide	narrow	wide
Full	Novice	S1-8	S1-8	S1-8	S1-8
	Expert	S9-16	S9-16	S9-16	S9-16
Upper	Novice	S17-24	S17-24	S17-24	S17-24
	Expert	S25-32	S25-32	S25-32	S25-32
Lower	Novice	S33-40	S33-40	S33-40	S33-40
	Expert	S40-48	S40-48	S40-48	S40-48

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Statistical results

Scanning speed

	F-ratio.	*p*	
Range delimeter (R)	2.2*	<0.05	main effects
Truncation (T)	0.4		
Experience (E)	5.5*	<0.05	
Menu Span (S)	216.0**	<0.01	
RxT	0.0		interactions
RxE	1.0		
RxS	3.0		
TxE	1.1		
TxS	14.8*	<0.05	
ExS	1.0		
RxTxE	0.0		
RxTxS	1.0		
RxExS	1.7		
TxExS	0.3		
RxTxExS	0.5		

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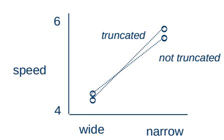
Statistical results

Scanning speed:

- Truncation x Span (TxS)



Main effects (means)

	Full	Lower	Upper
Full	----	1.15*	1.31*
Lower		----	0.16
Upper			----

Span:	Wide	4.35
	Narrow	5.54
Experience	Novice	5.44
	Expert	4.36

Main results on selection time

- Full range delimiters slowest
- Truncation has no effect on time
- Narrow span menus are slowest
- Novices are slower

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Statistical results

Error rate

	F-ratio.	*p*	
Range delimeter (R)	3.7*	<0.05	main effects
Truncation (T)	2.7		
Experience (E)	5.6*	<0.05	
Menu Span (S)	77.9**	<0.01	
RxT	1.1		interactions
RxE	4.7*	<0.05	
RxS	5.4*	<0.05	
TxE	1.2		
TxS	1.5		
ExS	2.0		
RxTxE	0.5		
RxTxS	1.6		
RxExS	1.4		
TxExS	0.1		
RxTxExS	0.1		

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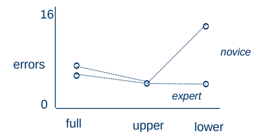
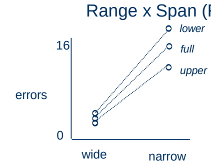
Statistical results

- Error rates
  - Range x Experience (RxE)



Range x Span (RxS)



- Results on error rate
  - lower range delimiters have more errors at narrow span
  - truncation has no effect on errors
  - novices have more errors at lower range delimiter
- Graphs: whenever there are non-parallel lines, we have a potential interaction effect

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Conclusions

- upper range delimiter is best
- truncation up to the implementers
- keep users from descending the menu hierarchy
- experience is critical in menu displays

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You know now

- Controlled experiments can provide clear convincing result on specific issues
- Creating testable hypotheses are critical to good experimental design
- Experimental design requires a great deal of planning
- Statistics inform us about
  - mathematical attributes about our data sets
  - how data sets relate to each other
  - the probability that our claims are correct

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You now know

- There are many statistical methods that can be applied to different experimental designs
  - T-tests
  - Correlation and regression
  - Single factor Anova
  - Factorial Anova
- Anova terminology
  - factors, levels, cells
  - factorial design
    - between, within, mixed designs

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For more information…

…I *strongly recommend* that you take EPSE 592: Design and Analysis in Educational Research

(Educational Psychology and Special Education)

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