Course "Empirical Evaluation in Informatics"

Controlled Experiments

Lutz Prechelt
Freie Universität Berlin, Institut für Informatik

- Example 1: flow charts
- Control and constancy
- Threats to constancy
- Techniques for achieving constancy
- Example 2: design pattern documentation
"Empirische Bewertung in der Informatik"

**Kontrollierte Experimente**

Prof. Dr. Lutz Prechelt
Freie Universität Berlin, Institut für Informatik

- Beispiel 1: Flussdiagramme
- Kontrolle und Konstanz
- Probleme für Konstanz

- Techniken zum Erreichen von Konstanz
- Beispiel 2: Entwurfsmuster-Dokumentation
Example 1: Flowcharts vs. Pseudocode


- Question: Is an algorithm easier to comprehend if presented as a flow chart or if presented as pseudocode?

- Study format: Controlled experiment
Flowchart, Pseudocode

- (These examples are not equivalent!)

```
PROC
  IF GREEN
    THEN
      BAKE
    ELSE
      BOIL
  IF CRISPY
    THEN
      STEAM
    ELSE
      FRY
  END IF
END PROC
```
Experiment rationale

- Earlier experiments by Shneiderman et al. on the same question had not found any differences

- Scanlan criticizes these experiments:
  - Have measured only correctness, not work time
  - Some questions could not be answered from flowchart alone
  - Program was too simple

- Scanlan attempts to create experiments without these flaws
Experiment setup

- Subjects: 82 MIS majors (junior to graduate)
- Independent variables (inputs):
  - program complexity/length: simple, medium, complex
  - presentation type: flowchart, pseudocode
  - therefore, there are $3 \times 2 = 6$ experiment groups
- Subjects study an algorithm and answer a fixed set of comprehension questions
  - 6*2, 9*4, 10*6 questions for simple, medium, complex alg.
  - Example questions:
    - "What are the values (true/false/unknown) at all decisions in the algorithm when the vegetable is boiled?"
    - "What are the values at all decisions in the algorithm when the vegetable is both boiled and steamed?"
    - (all questions are of this type)
- Experiment is run fully automatically
  - by a computer with speech output
Experiment setup (2)

- Flowcharts and pseudocodes are each printed on a single sheet of paper

- A mechanical machine switches between algorithm sheet and question/answer sheet
  - only one is visible at any time
  - subject can switch as s/he pleases

- Dependent variables (outputs):
  - algorithm view time
  - question answering time
  - number of algorithm views
  - percentage of correct answers
  - subjective confidence in the answers
Experiment setup (3)

- Each subject is part of all six groups
  - leads to $6 \times 82 = 492$ data points overall
  - This is possible because the algorithms use randomized combinations of verbs and adjectives
    - (What would be the problem otherwise?)
Complex algorithm

BEGIN

IF HARD THEN

ELSE

IF TALL THEN

ELSE

IF CRISPY THEN

ELSE

IF JUICY THEN

ELSE

GRILL

ELSE

BOIL

ELSE

BAKE

ELSE

BOIL

END IF

END IF

END IF

END IF

END IF

END IF

END IF

END IF

END IF

END IF

EXIT
Results

1. The subjects in the flowchart groups
   1. require less algorithm view time
   2. require much fewer algorithm views
   3. provide more correct answers
   4. have higher confidence in their answers

2. The differences tend to become more pronounced with increasing algorithm complexity
### Table A.
Percentage of correct answers to all question parts.

<table>
<thead>
<tr>
<th>Complexity level</th>
<th>IV</th>
<th>Total parts</th>
<th>% correct (means)</th>
<th>s</th>
<th>t</th>
<th>df</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple</td>
<td>FC</td>
<td>12</td>
<td>97.97</td>
<td>8.50</td>
<td>2.77</td>
<td>81</td>
<td>.0035</td>
</tr>
<tr>
<td></td>
<td>PC</td>
<td>12</td>
<td>93.80</td>
<td>10.90</td>
<td>2.77</td>
<td>81</td>
<td>.0035</td>
</tr>
<tr>
<td>Medium</td>
<td>FC</td>
<td>36</td>
<td>98.81</td>
<td>3.40</td>
<td>4.05</td>
<td>81</td>
<td>.0000</td>
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<tr>
<td></td>
<td>PC</td>
<td>36</td>
<td>94.92</td>
<td>10.30</td>
<td>4.05</td>
<td>81</td>
<td>.0000</td>
</tr>
<tr>
<td>Complex</td>
<td>FC</td>
<td>60</td>
<td>98.68</td>
<td>3.50</td>
<td>4.82</td>
<td>81</td>
<td>.0000</td>
</tr>
<tr>
<td></td>
<td>PC</td>
<td>60</td>
<td>91.71</td>
<td>14.40</td>
<td>4.82</td>
<td>81</td>
<td>.0000</td>
</tr>
</tbody>
</table>

*FC = flowchart; PC = pseudocode; IV = independent variable; s = standard deviation (in seconds); t = correlated t-test result; df = degrees of freedom; p = probability.*
Discussion: Internal validity / credibility

• The internal validity of this experiment is very high
  • We can be confident to find similar results if we repeated the experiment

• Problems avoided by this experiment setup:
  • accidental group differences
    • by using large groups and an intra-subject design
  • measurement errors
    • by fully automatic measurement mechanism
  • accidental experimenter influence on subject motivation
    • by fully automatic experiment guidance (speech output etc.)
  • and more
    • e.g. by using a shielded room, by having practice sessions

• The only remaining question:
  • Are the subjects equally well trained in both notations?
Discussion:
External validity / credibil.+relevance

- The external validity of this experiment is very problematic:
  - Issues with the structure of the algorithms
  - Issues with the meaning of the algorithms
  - Issues with the size of the algorithms
  - Issues with the number of questions (in relation to algorithm size)
  - Issues with the type/content of questions
### Table 1.
Number of seconds subjects looked at algorithm when answering each question part.

<table>
<thead>
<tr>
<th>Complexity level</th>
<th>Total parts to questions</th>
<th>Means (sec./part)</th>
<th>s</th>
<th>t</th>
<th>df</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple</td>
<td>FC</td>
<td>12</td>
<td>7.83</td>
<td>5.09</td>
<td>81</td>
<td>.0000</td>
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<tr>
<td></td>
<td>PC</td>
<td>12</td>
<td>13.44</td>
<td>7.75</td>
<td>6.47</td>
<td>81</td>
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<tr>
<td>Medium</td>
<td>FC</td>
<td>36</td>
<td>6.19</td>
<td>3.02</td>
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<td>.0000</td>
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<td></td>
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<td>36</td>
<td>11.71</td>
<td>6.50</td>
<td>9.43</td>
<td>81</td>
</tr>
<tr>
<td>Complex</td>
<td>FC</td>
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<td>6.33</td>
<td>2.37</td>
<td>81</td>
<td>.0000</td>
</tr>
<tr>
<td></td>
<td>PC</td>
<td>60</td>
<td>15.80</td>
<td>10.98</td>
<td>8.45</td>
<td>81</td>
</tr>
</tbody>
</table>

**FC** = flowchart; **PC** = pseudocode; **IV** = independent variable; **s** = standard deviation (in seconds); **t** = correlated *t*-test result; **df** = degrees of freedom; **p** = probability.
**Table D.**

Mean number of times the algorithm was viewed when answering each part of all questions.

<table>
<thead>
<tr>
<th>Complexity level</th>
<th>IV</th>
<th>Total parts</th>
<th>Times/part</th>
<th>s</th>
<th>t</th>
<th>df</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple</td>
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<td>12</td>
<td>1.30</td>
<td>.275</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PC</td>
<td>12</td>
<td>1.41</td>
<td>.344</td>
<td>3.25</td>
<td>81</td>
<td>.0008</td>
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<tr>
<td>Medium</td>
<td>FC</td>
<td>36</td>
<td>.86</td>
<td>.239</td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>PC</td>
<td>36</td>
<td>.92</td>
<td>.289</td>
<td>2.84</td>
<td>81</td>
<td>.0030</td>
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<tr>
<td>Complex</td>
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<td>60</td>
<td>.72</td>
<td>.229</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PC</td>
<td>60</td>
<td>.82</td>
<td>.296</td>
<td>4.55</td>
<td>81</td>
<td>.0000</td>
</tr>
</tbody>
</table>
Methodology of controlled experiments

- "Experiment": Latin 'experimentum' (attempt, trial, experience)
  - means to try something out, to manipulate the situation

- Control refers to the construction of a repeatable situation
  - rather than one that has many arbitrary or even unknown attributes
  - Assume the situation can be fully characterized by N attributes
  - Then we want to experiment with k of them (often k=1)
    - We manipulate them: These are the independent variables
    - If we keep the other N-k attributes constant
      - These N-k attributes are called extraneous variables
      - The purpose of control is achieving constancy
  - we understand the effects of changing the independent variables.
    - The effects are defined by the observed dependent variables
Constancy in the natural sciences

- In basic physics or chemistry it is often relatively easy to achieve constancy
  - Although it may be difficult to set the independent variables to the values one wishes to explore
    - e.g. temperature and pressure for nuclear fusion

- The most difficult problem historically is finding out what attributes are relevant
  - i.e. what is not just an unimportant extraneous variable
  - e.g. understanding the nature of infectious diseases
Constancy with human beings

• In contrast, whenever human beings are part of the experiment, constancy becomes extremely difficult:
  • No two human beings are the same
  • No one human being is the same over time (memory!)

• The only known approach to obtain constancy for the human-related attributes of an experiment is averaging:
  • Pick a large number of humans ("subjects") at random
  • Assign each to an experiment condition at random
  • Perform the experiment with each one
  • Use the average results per group: differences balance out

• It works, except for one problem:
  • Subject motivation may depend on the value of the experimental variable
    • e.g. design method A is considered more 'sexy' than B
Threats to constancy

- **Individual differences**
  - The largest and most important effect in most human-related informatics experiments
  - e.g. capability, endurance, motivation

- **History**
  - Long-running experiments are influenced by outside events

- **Maturation**
  - Subjects learn and change during an experiment

- **Instrumentation**
  - Human observers change during an experiment
  - Technical measurement infrastructure may also change

- **Mortality**
  - Not all subjects stay until the end of the experiment
    - and drop-out probability may be related to the experiment variable
Threats to constancy (2)

• Experimenter influence
  • Experimenter handles subjects of different groups (or the data collected about them) in a biased way

• Sequence effects
  • The influence if the same subject solves more than one task
    • The order can influence the results
  • E.g. learning, tiring, boredom

• Sophistication
  • If subjects understand what the experiment is trying to find out, that can influence the result
  • E.g. unrealistic focus on one aspect of a task

If any of these occur, they must occur equally (on average) in each experiment group
Constancy in medicine: double blind testing

- The averaging method for achieving constancy can be applied to perfection in drug testing
  - We want to compare two medicines A and B
    - Or even A to doing nothing: use a placebo
  - A subject does not know which one s/he receives ("blinding")
  - The doctor does not know which one s/he applies ("blinding")
  - This is called a "double blind" experiment
    - But mortality can still be a big problem

- Unfortunately this approach is almost never applicable in informatics
  - You cannot apply a technique without knowing
  - So we almost always need to consider motivation differences as a threat to constancy and hence to internal validity
Techniques for achieving constancy

- **Randomization**
  - balances individual differences to achieve constancy

- **Matching**
  - reduces the impact of individual differences, maximizes constancy

- **Counterbalancing**
  - compensates sequence effects
Randomization

- Subjects must not assign themselves to the experiment conditions based on personal preferences
  - May produce bias
  - e.g. the more capable subjects may be more interested in the design method that appears more 'modern'
    - whereas the less capable ones rather stick with the familiar

- Experimenters also must not assign subjects based on whatever kinds of preferences
  - May produce bias; e.g. may assign the more capable subjects to his/her favorite method – even unconsciously

- Random assignment is the only method for avoiding bias
  - But may be very difficult, e.g. because not all subjects have the required knowledge for all experiment conditions
    - Without random assignment, the study will be a quasi-experiment
Matching

- Random assignment needs not make each single assignment from the whole pool of remaining subjects
  - Instead, we may pre-group 'similar' subjects into j-tuples (for j experiment conditions) and randomize over one tuple at a time
  - This is called matching

- Matching may increase group similarity and may effectively reduce individual variation across the groups

- Example:
  - Order the subjects by expected design capability
  - Take the next best 2 at each time
  - Assign one to method A and one to B randomly

- Matched samples improve the sensitivity of statistical analysis
Counterbalancing

- Often subjects need to perform more than one task
  - because suitable subjects are rare,
  - because instructing them is expensive, etc.

- This will produce sequence effects
  - learning, tiring, etc.

- To compensate these effects:
  - Have the same number of subjects perform the tasks in each of all possible task orders
  - for each of the experiment conditions or orders of experiment conditions
    - usually realistic only for 2 tasks
Counterbalancing: example

A typical experiment plan in informatics is as follows:

- We want to compare design methods A and B
- We use two different tasks 1 and 2
- Each subject solves both tasks
  - Solving one task twice (once with each method) makes no sense
    - due to learning (sequence effect)
- Experiment groups:
  - (group: first task, second task)
    - G1: A1, B2
    - G2: A2, B1
    - G3: B1, A2
    - G4: B2, A1
Example 2: Design pattern documentation

- Prechelt, Unger, Philippsen, Tichy: "Two Controlled Experiments Assessing the Usefulness of Design Pattern Documentation in Program Maintenance", IEEE Transactions on Software Engineering, June 2002

- Situation: You have programs that use/contain design patterns. The programs (source code) are well commented, but no separate design documentation exists. Now the programs must be modified.

- Question: Does understanding and modifying the programs become easier if the design pattern usage is documented explicitly?
Experiment variable

- The independent variable of this is whether or not PCLs were added to an already well-documented program
  - PCL: Pattern Comment Line
    A comment section that explicitly describes how a particular program element participates in a pattern
  - Example: lines 484 and 485 are PCLs

```java
477    /**
478    NTTupleDisp2 displays NTTuple, where
479    1. Tuples with an empty telephone number are left out and
480    2. Tuples are sorted by (last)name
481    Using Tuple objects of other Tuple types results in
482    ClassCastException.
483    *** DESIGN PATTERN: ***
484    NTTupleDisp2 completes the **Template Method** newTuple()
485    of TupleDispA
486    */
487    final class NTTupleDisp2 extends TupleDispA {
```
Experiment tasks

- The subjects worked on two different programs
  - Phonebook: A trivial phonebook management application with two different views of the data
    - Uses the 'Observer' and 'Template Method' design patterns
  - And/Or tree: A library (plus simple application) for handling AND/OR trees of Strings
    - Uses the 'Composite' and 'Visitor' design patterns
- For each program they solved a set of 4 small comprehension and modification tasks
  - for which the patterns were relevant
Dependent variables

- The observed variables were
  - time: The total time for solving one task
  - quality: A grading (in points) of the submitted solution according to well-defined criteria
Experiment design

- **Nomenclature:**
  - A: And/Or tree, P: Phonebook,
  - +: with PCL added, -: without

- **Counterbalanced design:**
  - 4 groups: A+ P- A- P+
    P+ A- P- A+
  - Randomized assignment of subjects to groups
  - No matching
Subjects

The experiment was performed twice:

- **UKA**: 74 diploma students of University of Karlsruhe; programs in Java
  - prepared solutions on paper
    - incorrect answers produce no feedback → harder to detect

- **WUSTL**: 22 undergraduate students of Washington University, St. Louis; programs in C++
  - implemented solutions on Unix workstations

- All had taken a laboratory course on Java/C++ including design patterns
Results And/Or tree (difficult task)

- UKA: '+' is slower but much more often correct
  - Reason: wrong answers produce no feedback (work is on paper!)
- WUSTL: '+' is much faster

<table>
<thead>
<tr>
<th>Variable</th>
<th>mean with PCL</th>
<th>mean w/o PCL</th>
<th>means difference (90% confid.)</th>
<th>significance p</th>
</tr>
</thead>
<tbody>
<tr>
<td>UKA, program And/Or-tree:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 relevant points</td>
<td>8.5</td>
<td>7.8</td>
<td>$-7.7% \ldots + 23%$</td>
<td>0.20</td>
</tr>
<tr>
<td>2 #corr. solutions</td>
<td>15 of 38</td>
<td>7 of 36</td>
<td>$-3.0% \ldots + 24%$</td>
<td>0.077</td>
</tr>
<tr>
<td>3 time (minutes)</td>
<td>58.0</td>
<td>52.2</td>
<td>$-11% \ldots + 41%$</td>
<td>0.17</td>
</tr>
<tr>
<td>4 — corr. only</td>
<td>52.3</td>
<td>45.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WUSTL, program And/Or-tree:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 relevant points</td>
<td>6.7</td>
<td>6.5</td>
<td>$-12% \ldots + 19%$</td>
<td>0.28</td>
</tr>
<tr>
<td>6 #corr. solutions</td>
<td>4 of 8</td>
<td>3 of 8</td>
<td>$-43% \ldots - 0.5%$</td>
<td>0.046</td>
</tr>
<tr>
<td>7 time (minutes)</td>
<td>52.1</td>
<td>67.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Results phonebook (simple task)

- UKA: '+' is faster
- WUSTL: these results had to be discarded
  - because the subjects lacked knowledge of Observer pattern.
  - Also, the C++ version had no GUI, hence was unintuitive

<table>
<thead>
<tr>
<th>Variable</th>
<th>mean with PCL</th>
<th>mean w/o PCL</th>
<th>means difference (90% confid.)</th>
<th>significance p</th>
</tr>
</thead>
<tbody>
<tr>
<td>UKA, program Phonebook:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 relevant points</td>
<td>16.1</td>
<td>16.3</td>
<td>−8.0%...+ 4.0%</td>
<td>0.35</td>
</tr>
<tr>
<td>9 #corr. solutions</td>
<td>17 of 36</td>
<td>15 of 38</td>
<td>−22%...+ 0.3%</td>
<td>0.055</td>
</tr>
<tr>
<td>10 time (minutes)</td>
<td>51.5</td>
<td>57.9</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Discussion of internal validity

• Extraneous variables are controlled well by the counterbalanced design
  • even if groups were unequal, differences contribute equally to the experiment condition and the control condition

Problem:
• Quite some mortality in the WUSTL experiment
  • Very last event of the semester
  • "I have to catch my plane home"

• Fortunately, mortality in experiment and control groups is about equal
  • Has therefore probably not distorted the results
Threats to external validity

Differences to professional SW engineering contexts:

- **Subject experience/capabilities:**
  - Professionals may
    - have less need for PCL (would decrease effect) or
    - may make better use of PCL information (would increase effect)

- **Team work:**
  - May increase effect because patterns provide a common terminology; PCL allows for exploiting it

- **Program size:**
  - Larger programs may show a larger effect, as PCL provides program slicing information

- **Program and task representativeness:**
  - is unclear
Construct validity: Is 'no PCL' a good control group?

- It is surprisingly unclear what would be a valid experiment design for finding out whether "having design pattern information is useful" for maintenance:
  - Giving somebody program structure information (which somebody else does not have) will often help
    - but may have nothing to do with design patterns
  - Can the given comparison be considered fair?
Analysis of documentation content

- Analyzed which pieces of information are present how often in the documentation
  - here: for And/Or tree
- Identified 18 pieces (A-R), 4 of them crucial for solving the given tasks
- PCL is redundant: 17 pieces are present in non-PCL comments
  - incl. the 4 crucial ones A, B, L, M
- Therefore, the comparison is fair:
  - redundant information could also have hurt!
Description of some information pieces

<table>
<thead>
<tr>
<th>id</th>
<th>Design Information Unit (UKA And/Or-tree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>There is an <code>element/container structure</code></td>
</tr>
<tr>
<td>B</td>
<td><code>Element</code> is the superclass of the <code>element/container structure</code></td>
</tr>
<tr>
<td>C</td>
<td><code>Element</code> is abstract</td>
</tr>
<tr>
<td>D</td>
<td><code>AndElement</code> is a part of the <code>element/container structure</code></td>
</tr>
<tr>
<td>E</td>
<td><code>OrElement</code> is a part of the <code>element/container structure</code></td>
</tr>
<tr>
<td>F</td>
<td><code>StringElement</code> is a part of the <code>element/container structure</code></td>
</tr>
<tr>
<td>G</td>
<td>There are multiple <code>container classes</code></td>
</tr>
<tr>
<td>H</td>
<td><code>AndElement</code> is a <code>container class</code></td>
</tr>
<tr>
<td>I</td>
<td><code>OrElement</code> is a <code>container class</code></td>
</tr>
<tr>
<td>J</td>
<td>There is only one <code>element class</code></td>
</tr>
<tr>
<td>K</td>
<td><code>StringElement</code> is an <code>element class</code>*</td>
</tr>
<tr>
<td>L</td>
<td>There is an <code>iterator structure</code>*</td>
</tr>
</tbody>
</table>
Summary

• Controlled experiments apply the scientific method in its purest form:
  • Test whether an effect predicted by some theory is observed

• Control is for achieving constancy in the attributes that are not investigated (extraneous variables)

• Constancy is difficult to obtain with human subjects
  • They just differ so much!
  • The only way is repetition and averaging

• Other threats to constancy are history, maturation, instrumentation or experimenter effects, mortality, sequence effects, and sophistication

• Methods for improving constancy are randomization, matching, and counterbalancing
Thank you!