Scientific Thinking Skills

OUTLINE

* Definitions
  * Scientific Thinking vs. Scientific Understanding
* A Framework
* Scientific Thinking Skills
  * Experimentation
  * Evidence evaluation
  * Microgenetic studies of self-directed experimentation

Defining Scientific Thinking

<table>
<thead>
<tr>
<th>Scientific Understanding</th>
<th>Scientific Thinking</th>
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</thead>
<tbody>
<tr>
<td>Scientific Knowledge</td>
<td>Scientific Inquiry Skills</td>
</tr>
<tr>
<td>Product</td>
<td>Process</td>
</tr>
<tr>
<td>Concepts/misconceptions</td>
<td>Strategies</td>
</tr>
</tbody>
</table>

Why Do Psychologists Study Scientific Thinking?

* Understand cognitive development
  * Reasoning, problem solving, conceptual development, and metacognition
* Informs theories of cognitive development
* Informs science education
  * What are children capable of? At what age

A Framework

* How are studies of SR approached?
* The SDDS Model
  * Scientific Discovery as Dual Search
  * Klahr & Dunbar (1988); based on Newell and Simon’s work on problem solving
* Three broad phases:
  * Search hypothesis space
  * Search experiment space
  * Evidence evaluation
Scientific Discovery as Dual Search

From Klahr (2000)

SDDS Simplified

<table>
<thead>
<tr>
<th>Type of Cognitive Process/Phase of Scientific Inquiry</th>
<th>Hypothesis Generation</th>
<th>Design Experiment</th>
<th>Evidence Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domain Specific (Content)</td>
<td>A</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>Domain General (Process)</td>
<td>D</td>
<td>E</td>
<td>F</td>
</tr>
</tbody>
</table>

From Klahr (1994; 2000)

A Cyclical Process

Researchers can either study parts of the process or the entire process.

Typical studies:
1. experimentation skills
2. evidence evaluation
3. self-directed experimentation

(1) Experimental Design Skills

Selecting or designing an experiment to test a hypothesis.

Hypothesis Space
1. Selected by Ps
2. Given to Ps

Experiment Space
1. Forced choice
2. Free choice
(a) Can children select an empirical test to decide among competing hypotheses?

- Can children differentiate between a hypothetical belief and evidence?
- "Mouse House Task"
- Ps: 6-10 year olds
- Presented with conclusive vs. inconclusive tests
- Key Finding
  - Young children can select a conclusive test (with justification)

Sodian, Zaitchik & Carey (1993)

(b) Is the selection of an experimental strategy influenced by context?

- Manipulate variables to produce a conclusive test
- Logic vs. 'natural' problem solving
- Good vs. bad outcome
- Participants asked to choose one of 3 strategies:
  - VOTAT
  - HOTAT
  - CA

Tschirgi (1980)

"Everyday" Problem Solving

- John baked a cake with
  - sweetener (honey/sugar)
  - flour (white/wholewheat)
  - shortening (butter/margarine)

- The cake turned out great (or terrible)
- John thought that the reason the cake was so great (or terrible) was because of the honey
- What should he do to prove his point?

Testing the "honey" hypothesis...

Original recipe: honey, butter, white flour

- John can bake the cake again...
  a) but use sugar instead of honey and still use butter and white flour (vary one thing at a time)
  b) using sugar, margarine, and wholewheat flour (change all)
  c) and still use honey, but use margarine and wholewheat flour (hold one thing at a time)
Is the selection of an experimental strategy influenced by context?

- **Yes**
- Good outcome:
  - HOTAT
- Bad outcome:
  - VOTAT (i.e., the logical, control-of-variables strategy)

**Hypothesis**

**Space**

**Given to Ps**

**Experiment Space**

Forced choice (VOTAT, HOTAT, CA)

**Data/Evidence**

Evaluate (make inference)

Tschirgi (1980)

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(c) Is strategy selection influenced by prior belief?

- Scientific reasoning involves reasoning about natural or social phenomena
- Do our prior beliefs influence the selection of an experimental strategy?
- If so, do such beliefs influence experimental strategies as a function of the type of outcome?

**Hypothesis**

**Space**

**Given to Ps**

**Experiment Space**

Forced choice (VOTAT, HOTAT, CA)

**Data/Evidence**

Evaluate (make inference)

(Croker & Buchanan, 2008)

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**Outcome consistent with prior belief**

Good outcome

Bad outcome

(Reversed for Belief-inconsistent Condition)

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**The interaction of outcome and prior belief**

<table>
<thead>
<tr>
<th></th>
<th>Good outcome / belief-consistent</th>
<th>Good outcome / belief-inconsistent</th>
<th>Bad outcome / belief-consistent</th>
<th>Bad outcome / belief-inconsistent</th>
</tr>
</thead>
<tbody>
<tr>
<td>% trials</td>
<td>80</td>
<td>70</td>
<td>60</td>
<td>50</td>
</tr>
</tbody>
</table>
(d) Does context influence the design of experiments in a classroom assessment?

* The main objective of the Experiments with Plants curriculum unit is to teach children (age 11-12) how to design and conduct controlled investigative experiments.

* Two cover stories:
  * Test the claim that coffee grinds are “good” for plants
  * Test the claim that tap water is “bad” for plants

* Three questions:
  * Describe how you would set up the experiment. You may draw pictures along with your explanation.
  * Describe what you would measure.
  * Design a table to record the data collection throughout your experiment.

(From Zimmerman & Glaser, 2001)

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Performance differences:

<table>
<thead>
<tr>
<th>Process Skill</th>
<th>% Testing a Positive Claim</th>
<th>% Testing a Negative Claim</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manipulate the correct variable</td>
<td>23</td>
<td>79</td>
</tr>
<tr>
<td>Manipulate only one variable</td>
<td>23</td>
<td>100</td>
</tr>
<tr>
<td>Use of repeated measures</td>
<td>54</td>
<td>86</td>
</tr>
<tr>
<td>Systematic observation</td>
<td>54</td>
<td>71</td>
</tr>
<tr>
<td>Keep conditions constant</td>
<td>15</td>
<td>21</td>
</tr>
</tbody>
</table>

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Summary: Experimental Design Skills

* Children as young as 6 can differentiate between a conclusive and inconclusive test of a hypothesis.

* The choice of the logically correct correct strategy (VOTAT) depends on:
  * Prior knowledge
  * Outcome (producing good or bad effects)

* What develops?
  * Epistemological understanding
  * Metacognition

(2) Evidence Evaluation

Given a set of data/evidence, what inferences are drawn?

Evaluate (make inference) → Hypothesis (knowledge, belief, theory) → Data/Evidence Given to Ps
Theory-Evidence Coordination

* Type of theoretical claims
  * T1: Category claim
  * T2: Event claim
  * T3: Causal or explanatory claim
  * T4: Explanatory system claim (Kuhn & Pearsall, 1998)

* (1) Inductive causal inference
* (2) Recognition of **theory** and **evidence** as distinct epistemological categories

(a) How do individuals reconcile prior beliefs with new evidence?

* Covariation evidence
  * Confirm existing belief
  * Disconfirm existing belief
* Presentation of evidence
  * Covariation or non-covariation between eating different types of food and susceptibility to catching colds
* Responses
  * Data-based
  * Theory-based

Coordinating evidence and theory

* **Evidence** = patterns of covariation/non-covariation; empirical observations
* **Theory** = any claim that can be evaluated by appealing to empirical evidence

**Key Findings**

* Strategies for keeping theory and evidence aligned
  * Ignoring evidence
  * Distorting evidence
  * Selectively attending to evidence
  * Adjusting theory to fit evidence (i.e., without awareness of theory change)

* Developmental trends
(b) Can children coordinate theory and evidence with reduced task demands?

- Participants given patterns of covariation data (4-7 year-olds)
- One cause (food type)
- One effect (tooth loss)
- 6-year-olds could form a hypothesis about a causal factor from evidence
- By age 7, children understand the new hypothesis can be used to make predictions

Ruffman et al., 1993

(c) Correlation does not imply causation

- Evidence evaluation is done in conjunction with (i) prior knowledge, (ii) considerations of plausibility, and (iii) concern for causal mechanisms/theory
- There is an interdependence of theory and evidence
- Theory and evidence bootstrap one another in authentic scientific thinking

Koslowski (1996)

- Series of 16 experiments to demonstrate the legitimacy of using theory in scientific reasoning
- Theory: incorporates ideas of covariation, causal mechanism, plausibility, and possible alternative causes

(1) Directed Inquiry

Summary – Evidence Evaluation

- Inductive causal inference vs. epistemological understanding
- Prior knowledge and a concern for theory influence the evaluation of new evidence
- Developmental trend in evidence-based justifications: bracketing prior belief
- Developmental trends in representing theory and evidence as distinct

(2) Self-Directed Experimentation

How do children negotiate the entire cycle of inquiry?

What changes in knowledge and strategy use are evident with extended practice?
### Microgenetic Studies

<table>
<thead>
<tr>
<th>Hypotheses Space Search</th>
<th>Experiment Space Search</th>
<th>Evidence Evaluation</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assessment of initial beliefs</td>
<td>Selection of variables/levels</td>
<td>Inferences; Causality/inclusion; Non-causal; Indeterminate; False Inclusion</td>
<td>Transfer Retention</td>
</tr>
<tr>
<td>Type of hypotheses selected (e.g., plausible, causal, single/multiple)</td>
<td>% E-space Strategies: CVS (VOTAT); HOTAT; CA</td>
<td>Justifications: Theory-based vs. evidence-based</td>
<td></td>
</tr>
<tr>
<td>Predictions / Intentions / Plans</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Record keeping / Record consulting</td>
<td>Successful knowledge acquisition</td>
<td></td>
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### Tracking the development of knowledge and strategies

**Example microgenetic study** (Schauble, 1996)
- 10/11yr olds, adults; 6 weeks
- Effects of variables on speed of boats (hydrodynamics)
  - Depth of canal, shape of boat, boat size, weight
- Effects of variables on spring length (hydrostatics)
  - Object position, object volume, object weight
- Key Finding:
  - Domain-specific knowledge and domain-general strategies bootstrapped one another, either alone did not guarantee task success

### Individual Differences

**Experimenter (Theory Generating)**
- No stated expectations; systematic: controlled tests of each variable;
- Induce rule/hypothesis/theory

**Theorists (Theory Preserving or Theory Modifying)**
- Explicitly stated expectation, controlled tests and “try-and-see”; evidence evaluation depends on experimentation strategy
- Theory modified (or not) based on exploration

**Scientists (goal = understanding)**
- Concern with causal and non-causal variables;
- Theory-driven approach: generating or modifying

**Engineers (goal = optimization)**
- “Try-and-see” approach: highly contrastive combinations, ignore variables believed non-causal
Summary of Findings – Microgenetic Self-Directed Experimentation

* Hypothesis Search
  * Children focus on causal, plausible
  * One hypothesis at a time; often no explicit hypothesis

* Experiment Search
  * Selecting variables depends on (i) perceived goal; (ii) positive or negative outcomes; desired outcomes
  * Redundant experiments; demonstrate beliefs
  * Children less likely to use CVS/VOTAT, but learn with practice

* Evidence Evaluation
  * Focus on causal inferences; false inclusion
  * Make inferences based on insufficient evidence
  * Practice necessary to focus on non-causal; indeterminate

* BOOTSTRAPPING

Knowledge Change/ Acquisition

* Prior belief (or expectation) matters
  * Causal to non-causal or vice-versa
  * Anomalies promote conceptual change but only when they are noticed

* Content (what is being reasoned about) Matters
  * Outcome (good/bad; perceived goal)
  * Domains (e.g., social vs. physical; Agentic vs. non-agentic)

Learning Outcomes

* Understand the difference between scientific thinking and scientific knowledge

* Understand how scientific thinking skills give rise to scientific knowledge (and vice versa) via the bootstrapping hypothesis

* There is a difference between cognitive competencies on scientific thinking tasks and metacognitive and/or metastrategic competencies

* Scientific thinking has a long developmental trajectory

The Learning Cycle in Science Education