Title
Attentional Heuristics in Human Thinking

Journal
Proceedings of the Annual Meeting of the Cognitive Science Society, 6(0)

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Publication Date
1984

Peer reviewed

Attentional heuristics in human thinking

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1. Introduction

Several mechanisms have been proposed to explain human thinking, such as heuristic search [4], restructuring [6], deduction [2], etc. In this paper I propose that the *allocation of attention* is the major determinant of the course of human thought processes. Furthermore, I argue that this idea is implied by two known properties of the human cognitive architecture, namely the limited capacity of working memory and the inability to inspect procedural knowledge. It follows that strategies for thinking must contain heuristics for how to allocate attention. In consequence, simulation models of human thinking cannot afford to ignore perceptual interaction with the environment. Several examples of attentional heuristics are discussed.

2. Attention and Architecture

The purpose of this section is to derive the importance of attention from principles about the human cognitive architecture. The following definitions set the stage for the argument. Let us use *cognitive unit* generically to cover concepts, propositions, mental images, hypotheses, frames, or any other declarative representational device that may be needed in a theory of thinking. Similarly, let *cognitive operation* stand for rules of inference, problem solving operators, or any other unit of procedural knowledge. Let a *stimulus unit* be any part of the environment that is represented by a single cognitive unit. Let *working memory* at time *t* be the set of cognitive units in the problem solver's awareness at time *t*. The process of (visually) *attending* to a stimulus unit consists of moving the eye to that unit, and creating the corresponding cognitive unit in working memory. Information *integration* is any process in which two or more cognitive units are combined to create a new cognitive unit, as when two or more propositions are used as premises from which a new proposition is inferred.

The first part of the argument makes use of the familiar architectural principle that *working memory can only hold a certain number of cognitive units at any one time*. The cause of this capacitly limitation is not important for present purposes. The present argument requires only that there is some limit on the number of units that can be added to working memory at any one time without loss of existing units. The following sequence of assertions connect working memory capacity with attention:

- For many problems, the given information consists of more units than can be held in working memory simultaneously; therefore, the thinker necessarily attends only to a subset of them at any one time.
- In order to solve a problem, cognitive units must be integrated; a task which requires no information integration is almost by definition not a thinking task.
- In order to be integrated, two units must be in working memory at the same time.
- Since the eye can only focus on one stimulus unit at a time, cognitive units will arrive sequentially in working memory.
- Therefore, the order in which stimulus units are attended determines which units can be integrated, and thereby affects the possibility of solving the problem.

For example, suppose that the integration of units *A* and *B* is a necessary step in the solution, and that *A* is attended to. For integration to occur, *B* must become attended before *A* has been forgotten. If the number of units attended to between *A* and *B* is too large, *A* may be lost before *B* arrives in working memory, preventing or delaying the solution. If the problem consists of, say, 10 units, there are 10!, or more than 3.5 million different orders in which the elements can be attended to, assuming that each element is attended once. (If an element can be attended more than once, the number of different orders is larger.) Unless the thinker has some rules to guide the allocation of attention, he/she can search for a long time before *A* and *B* appear simultaneously in working memory.

In conclusion, the limited capacity of working memory implies that a thinker must have rules for which stimulus units to attend to when solving a particular type of problem, and in which order to attend to them. Such rules will be called ***attentional heuristics***. Examples will be given in the next section.

The next part of the argument makes use of a second familiar architectural principle: *Humans have limited knowledge about their knowledge; in particular, they do not know which cognitive operations they are capable of, nor do they know what the legal conditions or the outputs of those operations are.* In other words, procedural knowledge tends to be ***opaque***. The stock example of our inability to inspect procedural knowledge is our lack of insight into the grammatical knowledge that we use in understanding natural language. The opaqueness of inferential knowledge is confirmed by work on expert systems. Extracting rules from a human expert takes a long time, and requires many revisions of the rule set. Experts have little explicit knowledge of the inferential rules they possess.

The opaqueness of procedural knowledge has several effects. First, the thinker cannot anticipate what the result would be of applying a particular cognitive operation without executing it. Being unable to retrieve the operation and inspect its "code", the thinker cannot reason at a meta-level about the operation. Second, since the thinker does not know which cognitive operations he/she has available, he/she cannot choose to execute a particular operation. A system with opaque knowledge must evoke its operations in a data-driven fashion, each operation keeping a look-out for a cognitive unit which can serve as input, and going into action when one is found. In such a system, the application of operations is controlled by the allocation of attention.

The above argument is summarized in the following *principle of attentional control of thinking*:

- A human thinker cannot intentionally apply cognitive operations, he/she can only intentionally select which stimulus unit to attend to at any one moment in time. A new conclusion, problem solving step, insight, etc, may or may not flow from the attended information. As a result, the thinker's control over his/her cognitive activity is indirect: which operations are applied and in what order is a function of the attended information. Success in thinking requires that units are attended in such an order that the necessary integrations can occur.

According to this principle, skill in thinking consists in knowing what to look at, and when to look at it. The next section gives examples of heuristics which encode such knowledge.

3. Examples of attentional heuristics

3.1. Verbal reasoning

In an analysis of 60 think-aloud protocols from a verbal reasoning task with spatial content, Ohlsson [5] found that out of 2520 identifiable problem solving steps, 1255 or 47 % were steps in which a premise was read from the problem text. The following ten attentional heuristics were postulated to account for such steps:

1. Begin solving the problem by reading the first premise.
2. Begin by reading the question.
3. When all premises have been processed, then read the question.
4. When there is nothing else to do, read from the problem text.

5. When a new conclusion has been arrived, read from the problem text.
6. If the last premise read was premise *N* , then read premise *N + 1*.
7. Read a premise which has not been read yet.
8. Select an object about which an inference recently was made, and read a premise which mentions that object.
9. Select an object about which no inference has yet been made, and read a premise which mentions that object.
10. Select an object that is remembered as interesting, and read a premise which mentions that object.

The heuristics fall into three distinct classes: rules 1-3 deal with the first and last acts of reading, rules 4 and 5 determine *when* it is appropriate to read (rather than do something else), and rules 6-10 specify *what* to read.

Each subjects was modelled by a different subset of these attentional heuristics. For example, the behavior of one subject was modelled well by heuristics 1, 5, and 6, while another subject seemed to behave according to rules 2, 4, 7, and 8. In short, interindividual differences in the allocation of attention were clearly visible in the protocols.

3.2. Classical mechanics

In a study of problem solving in classical mechanics, Larkin and co-workers [3] found that a major difference between novice and expert problem solving was the order in which the equations of a problem were used. Novices tended to work backwards, from the desired quantity to the given ones, while experts tended to use the equations in a forward search fashion, going from the given to the desired quantitites. Re-formulating these strategies as attentional heuristics, we have:

1. Attend to equations which contain many known quantities.
2. Attend to equations containing the desired quantity.

The similarity between these two heuristics and heuristics 8 and 9 in the previous example should be noted. Rule 1 (and 8 above) represent a *chaining* tactic: having processed an object (premise, variable, etc.), the thinker looks for further information about that object; in so doing, he/she encounters other objects which are then processed; etc. Rule 2 (and 9 above) represent a *missing part* tactic: look for objects about which nothing is known yet. These heuristics seem to be very general. Also, they nicely illustrate the nature of heuristics: both are useful, although they give contradictory advice.

3.3. Other examples

In a simulation study of chess perception, Simon and Barenfeld [8] found that the eye-movements of chess players could be predicted from the number and character of the chess-relations entered into by a particular chess piece. The attentional heuristic of the players could be formulated as "look at pieces which enter into many important chess relations".

In his studies of children's conservation of physical quantitites, Piaget [1] hypothesized that children fail to conserve because they do not coordinate compensating changes in objects. The attentional heuristic non-conserving children lack might be formulated as "attend to all changed dimensions of the object to be judged".

In a study of problem solving in geometry, Ohlsson [7] found that success in finding proofs was dependent on attending to the right geometric objects. When confronted with a figure which contained several different triangles, the subjects had no heuristics for which triangle to attend to. However, one subject had the heuristic "when stuck, try to discover new geometric objects in the figure".

4. Discussion

To restate the main idea, success in thinking is often a matter of knowing where to look; once the right subset of the available information is attended to, it is often self-evident what step to take or which conclusion to draw. Conversely, if the right information is not attended to, achieving the solution may be impossible. Human thought is therefore mainly governed by attentional heuristics.

The validity of this conclusion can be expected to vary across task domains. In domains where all relevant problem information can be kept in mind simultaneously, attentional heuristics become less important, because no selection is involved. Similarly, in task domains where the thinker has explicit representations of his/her operations (eg mathematics), the latter need not be invoked in a data-driven fashion. On the other hand, in domains with information-rich displays and large amounts of irregular, intuitive, and informally acquired inferential knowledge, attentional heuristics can be expected to be the major determinant of behavior.

Attention allocation is not proposed here as an *alternative* to other mechanisms of thought. The theory of thinking certainly has to make room for mechanisms such as heuristic search, restructuring, deduction, analogy, etc. But such mechanisms are dominated by attention in the sense that they operate upon attended information, and they can only succeed to the extent that the right information has been attended.

Psychological theories often treat thinking separate from the perceptual-motor interaction with the problem situation. Simulation models of thinking usually assume that the problem has been encoded, and that all given information is available in working memory. But in task domains where attention allocation is the major determinant of thinking, simulation models cannot ignore perceptual interaction with the environment without ignoring a major part of the behavior to be simulated.

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