Quantifying Simplicity: How to Measure Sub-Processes and Bottlenecks of Decision Strategies Using a Cognitive Architecture

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Introduction

What makes a decision strategy simple or complex? In this project, we investigated the time costs for cognitive sub-processes and bottlenecks of decision strategies. In order to gauge these time costs, we formally implemented two prominent decision strategies as well as a working memory (WM) load manipulation within the cognitive architecture ACT-R (Anderson, 2007) and compared the performance of the strategies under varying degrees of WM load. We tested the simulation results from this analysis in an empirical study.

The first tested strategy is *tallying* (TALLY), which integrates across several attributes to make a decision (Gigerenzer & Goldstein, 1996). The second strategy is the *take-the-best* heuristic (TTB), which relies on one best attribute (or reason) and considers further attributes only if the decision alternatives do not differ on that reason. As TTB does not integrate across multiple attributes and often searches only part of the information, it is considered a relatively "simple" strategy (Gigerenzer, Todd, & the ABC Research Group, 1999).

Using TALLY and TTB as paradigmatic examples of integrative and one-reason decision making strategies, respectively, we evaluated the hypothesis that integrative strategies induce higher cognitive costs than one-reason strategies—as indicated, for instance, by longer response times and lower execution accuracy when set under WM load (cf. Payne, Bettman, & Johnson, 1993).

Methods

In a dual-task paradigm, one group of participants were instructed to make decisions using TALLY and another group using TTB while being set under WM load by a concurrent tone-counting task.

Decision Task and Strategy Instruction

The decision task was to infer which of two animals has a longer lifespan based on five biological attributes displayed as visual symbols. One group of participants (n = 42) was instructed to use TALLY, which examines all attributes and integrates the attributes in favor of each alternative; the other group (n = 42) was instructed to use TTB—the strategy that justifies decisions with one attribute and only examines more attributes when the decision alternatives do not differ on the current attribute.

To investigate the behavior of TTB in face of varying search requirements, we varied the number of attributes that needed to be searched before a difference between the alternatives could be detected (1-5 attributes).

Working Memory Load

In the concurrent tone-counting task, participants counted the number of times bird voices were played. To induce increasing amounts of WM load, there were either none, one, two or even three different kinds of bird voices. The tones started before the decision information became available and continued until a decision was made in the decision task. Thereafter, it had to be indicated how often the voice of each bird species had been played.

Computational Models in ACT-R

We implemented computational models for the decision strategies and the concurrent counting task in ACT-R 6.0. The models pursue the goals for the decision and tone-counting task, handling multi-tasking demands using Threaded Cognition (Salvucci & Taatgen, 2008). Specifically, the models for the decision strategies (i.e., TALLY and TTB) and for the tone-counting task all rely on ACT-R's problem state and retrieval module, as well as on the procedural module to progress through the course of their tasks (cf. Borst, Taatgen, & van Rijn, 2010).

The models store the information relevant for the two tasks in separate chunks that are either in the problem state (i.e., the buffer of the imaginal module) or need to be retrieved from declarative memory (i.e., when the other task was using the problem state). We modeled effects on reaction times and accuracy in terms of retrieval activity in both tasks using a combination of (a) decay in base-level activation, (b) spreading activation, and (c) chunk confusion via noise.

From the models we extracted time costs for (a) cognitive sub-processes (i.e., the amount of time that the constituent models rely on a specific cognitive resource corresponding to an ACT-R module), and (b) the bottlenecks they impose on cognitive processing (i.e., the amount of time that the models rely on a specific resource and no other process is executed in parallel).

Results

The modeling results showed that TTB produced faster response times than TALLY when WM load was not present or low and only little information had to be searched to make a decision. When WM load was higher and TTB had to inspect more attributes, however, the decision times of TTB increased strongly and exceeded those of TALLY. Both strategies could be applied with high accuracy that only decreased slightly under WM load. The concurrent task was also executed with high accuracy, although accuracy slightly declined for TTB when more attributes were inspected. Importantly, these patterns of results also emerged in the empirical study.

The computational models made it possible to attribute the performance differences of the strategies to the component cognitive sub-processes in both tasks, revealing bottlenecks to processing: When WM load is high and many attributes have to be inspected, the TTB model spends more time retrieving information from memory, updating WM, and coordinating the mental actions for decisions and the concurrent task compared to the TALLY model.

Another difference between the strategies is that TTB performs an ordered visual search for the next best attribute when the previous attribute did not discriminate between the alternatives; TALLY, by contrast, requires no ordered search as it examines all attributes irrespective of their order. Indeed, visual processing demands imposed time costs and bottlenecks to both models and increased for the TTB model as TTB's search requirements increased. However, these time costs for visual processes did not account for the extended decision times under WM load in any of the models.

Discussion

The results point to differential cognitive costs of paradigmatic examples of one-reason (i.e., TTB) and integrative (i.e., TALLY) strategies. These differences become most evident when more information needs to be searched and the resources for WM are occupied by another task (i.e., tone-counting), revealing conditions under which TTB imposes greater demands on WM than does TALLY.

In this project we used computational models to reveal the cognitive costs of decision strategies under varying internal (i.e., WM load) and external (i.e., search requirements) circumstances. We conceptualized the complexity of decision strategies in terms of time costs for cognitive sub-processes and bottlenecks for cognitive processing. In doing so, we gain novel insights into the cognitive complexity (or simplicity) of strategies. The project therefore extends the concept of building blocks of decision strategies (e.g., Gigerenzer et al., 1999), allowing to quantify the simplicity of "simple heuristics" and to compare it across different decision strategies.

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