

Characterizing Cognitive Adaptability via Robust Automated Knowledge Capture

Robert G. Abbott and J. Chris Forsythe

Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM 87185, USA
{rgabbot, jcforsy}@sandia.gov

Abstract. Applications such as individually tailored training and behavior emulation call for cognitive models tailored to unique individuals on the basis of empirical data. While the study of individual differences has been a mainstay of psychology, a prevailing assumption in cognitive theory and related modeling has been that cognitive processes are largely invariant across individuals and across different conditions for an individual. Attention has focused on identifying a universally correct set of components and their interactions. At the same time, it is known that aptitudes for specific skills vary across individuals and different individuals will employ different strategies to perform the same task [3]. Moreover, individuals will perform tasks differently over time and under different conditions (e.g. Taylor et al, 2004). To reach their full potential, systems designed to augment cognitive performance must thus account for such between- and within-individual differences in cognitive processes. We propose that cognitive adaptability is a trait necessary to explain the inherently dynamic nature of cognitive processes as individuals adapt their available resources to ongoing circumstances. This does not imply a “blank slate;” humans are predisposed to process information in particular ways. Instead, we assert that given variation in the structure and functioning of the brain, there exists inherent flexibility that may be quantified and used to predict differences in cognitive performance between individuals and for a given individual over time. This paper presents an early report on research we are undertaking to discover the dynamics of cognitive adaptability, with emphasis on a task environment designed to evoke and quantify adaptation in controlled experiments.

1 Cognitive Adaptability in Cognitive Modeling

While the study of individual differences has been a mainstay of psychology, a prevailing assumption in cognitive theory and related modeling has been that cognitive processes are largely invariant across individuals and across different conditions for an individual. Attention has focused on identifying a universally correct set of components and their interactions. Between-subject and within-subject variability is generally regarded as measurement error.

At the same time, it is known that aptitudes for specific skills vary across individuals and different individuals will employ different strategies to perform the same task [e.g. 3]. Moreover, individuals will perform tasks differently over time and under different conditions (e.g. Taylor et al, 2004). To reach their full potential, systems

designed to augment cognitive performance must thus account for such between- and within-individual differences in cognitive processes.

We propose that *cognitive adaptability* is a trait necessary to explain the inherently dynamic nature of cognitive processes as individuals adapt their available resources to ongoing circumstances. This does not imply a “blank slate;” humans are predisposed to process information in particular ways. Instead, we assert that given variation in the structure and functioning of the brain, there exists inherent flexibility that may be quantified and used to predict differences in cognitive performance between individuals and for a given individual over time.

2 Testing and Characterizing Cognitive Adaptability

A fundamental challenge in establishing cognitive adaptability is modeling individuals’ relative strengths and weaknesses, and tendencies to adopt different strategies. Unfortunately, tools that permit human knowledge and behavior to be automatically modeled at a level of individual specificity have largely been ignored within the cognitive neurosciences. Automated Knowledge Capture (AKC) is the most promising avenue for efficiently supplying cognitive models tailored to differences relevant to performance, decision making, and learning in complex environments.

Sandia National Laboratories, the University of Memphis, the University of Notre Dame, and the Mind Research Network are undertaking a study to test two foundational hypotheses of cognitive adaptability:

- Hypothesis 1: For a given task, individuals will exhibit different strategies with the specific strategy employed being a product of their intrinsic skills.
- Hypothesis 2: Individuals will exhibit varying levels of adaptability with an individual’s adaptability determining their propensity to switch strategies in response to changing circumstances.

To test these hypotheses, we are developing AKC techniques to allow us to characterize cognitive adaptability. Specifically, we will develop techniques to: (1) model patterns of selective information retrieval; (2) detect strategic biases revealing beliefs and intrinsic skills; (3) detect shifts in strategy over time; (4) develop mathematical techniques to bound the uncertainty in the individual cognitive models derived through AKC. We further intend to conduct experimental studies to establish neural correlates of behavioral metrics for cognitive adaptability.

3 Related Work

The study of individual differences has been a mainstay of psychology. Accordingly, a variety of traits, personality factors and performance dimensions have been discussed [2]. More recently, attention has focused on identifying neuro-physiological correlates of individual differences (e.g. Gevins & Smith, 2000). While psychological theories commonly accommodate individual differences and some focus on explaining covariance in psychological measures across individuals, attention is generally

focused on specific traits, as opposed to generalized mechanisms that account for individual differences across a range of different dimensions. Furthermore, representations of cognitive theory within computational cognitive models have provided provisions for adjusting various model parameters, but have offered little logic for adjustments beyond fitting the model to data obtained from a given experimental study [1; 5].

A central premise of the Cognitive Adaptability is that individuals differentially deploy their cognitive resources in response to ongoing circumstances. The same basic idea appears within other conceptualizations such as: Cognitive Continuum Theory (Dunwoody et al, 2000), which addresses judgments; Self-Organizing Cognition and dynamical systems approaches (Tschacher & Scheier, 1996; Tschacher & Dawwalder), which have been more heavily influenced by computer science than experimental cognitive research; and control theory applications to cognition (Jordan, 2000) which are based on engineering constructs that do not readily translate to biological systems.

4 Project Outline

Initial experiments will use a simple task in which subjects reproduce a line drawing within experimental conditions that place different demands upon their cognitive resources (e.g. retaining an image in working memory) or impose different task contingencies (e.g. different payoffs for speed vs. accuracy). Prior to experimental testing, separate measures will establish subjects proficiency for intrinsic skills associated with the experimental task (e.g. drawing precision, ability to handle mirror transformations) and personal biases (e.g. tendency to pursue high versus low risk rewards). Additionally, subjects' cognitive adaptability will be assessed using a response set switching paradigm (i.e. assessment of subjects' differential capacity to recognize that the rules governing a task have changed and adjust their behavior accordingly). It is hypothesized that for a given experimental condition, subjects will employ strategies that emphasize their individual cognitive strengths and biases. Furthermore, a subject's tendency to adopt strategies that emphasize skills for which they are less proficient or are contrary to their personal biases will vary in accordance with their cognitive adaptability. In the second year, the same paradigm will be employed but with a more complex task (the NASA Multi-Attribute Task Battery) that requires not only spatial skills, but also verbal processing, memory, and reasoning.

Current approaches for modeling cognitive task performance will be elaborated to encompass how an individual allocates their attention in performing a task. The resulting cognitive model will actively retrieve information from the task environment and exhibit information biases observed in the individual. To support automated knowledge capture, the task environment will be instrumented to include nonintrusive behavioral sensors such as eye tracking, posture recognition, mouse and keyboard manipulations, as well as a capacity to extract information from the graphical display including symbols, text, spatial positions and optical flow (i.e. movement of display elements in relation to one another).

5 Pilot Study

This section describes a pilot study of the line drawing task currently underway. The objectives of this study are 1) characterize strategies for the line drawing task, and 2) determine whether individual strategies correlate to aptitudes measured with a battery of standard psychometrics.

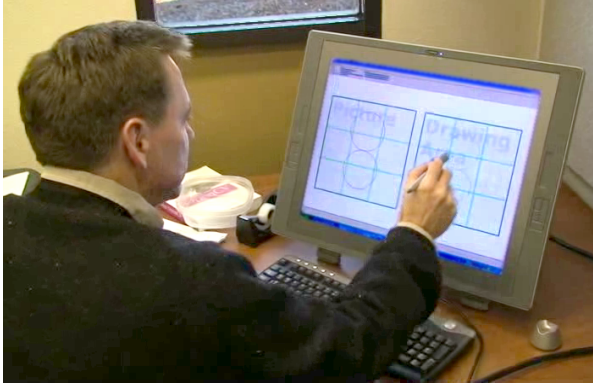


Fig. 1. A subject performing the line drawing task. Each subject in our pilot study draws for approximately 45 minutes.

5.1 Apparatus

The line drawing task is performed on a Wacom Cintiq 21UX interactive pen display. The display is approximately 43 cm wide by 33cm tall, however the drawing task is performed in a subregion approximately 22cm by 22cm. The resolution is 1200 rows and 1600 columns of pixels. This display was selected for its relatively large display/drawing area and low-latency response time (27ms claimed). All inputs are performed with the pen; the mouse and keyboard are not used by subjects in the experiment.

5.2 Drawing Task

Line drawing is performed in a software application shown in Fig. 2. The Picture Area (left) displays a figure to draw, while the Drawing Area (right) receives input. The picture need not be continuous and the subject may lift the pen and resume drawing at any time. The subject indicates completion of the trial by tapping outside the Drawing Area. Then the score for the trial is displayed briefly, then the task advances to the next trial. All of the settings described below are configured on a per-trial basis, so they can vary parametrically or randomly within a block of trials. An experiment session contains several blocks of trials. The order of blocks is randomized.

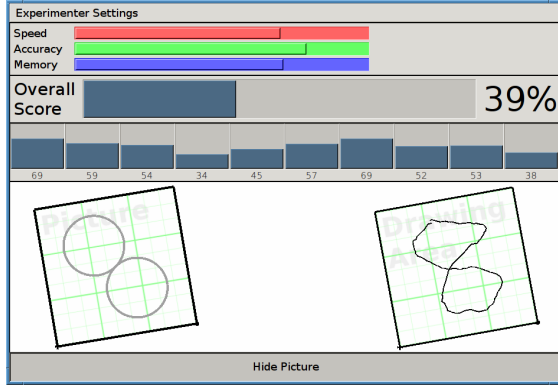


Fig. 2. The drawing task supports a variety of input and feedback conditions to elicit strategy shifts between and within subjects

5.3 Task Feedback

The task environment continuously scores each trial as the subject draws. There are three sub-scores and an overall score. Optionally, the scores are displayed and continuously updated to influence strategy selection.

- **Accuracy:** given sets of points $p_i \in P$ and $d_i \in D$ for the picture and drawing, respectively, with $0 \leq p_{i_x}, p_{i_y} \leq 1$ (and likewise for d_j) an accuracy score s_A is assigned according to Equation 1. The parameter τ determines how “strict” the metric is, with $\tau = 500$ a typical value. $\|p_i, D\|$ denotes $\min_{d_j \in D} \sqrt{(p_{i_x} - d_{j_x})^2 + (p_{i_y} - d_{j_y})^2}$ the distance from point p_i to the nearest point in set D , and $|P|$ is the number of points in set P .

$$s_A \equiv \left(1 - \frac{\sum_i \|p_i, D\|^2 + \sum_i \|d_i, P\|^2}{|D| + |P|} \right)^\tau \quad (1)$$

- **Speed:** the speed score s_S is a decay function of t , the duration of the trial, with parameter $t_{1/2}$ specifying the number of seconds before the score decays to 0.5 (Equation 2):

$$s_S \equiv \left(\frac{1}{2} \right)^{\frac{t}{t_{1/2}}} \quad (2)$$

- **Memory:** the memory score s_M is also defined by Equation 2, but taking the place of t is t_v , the number of seconds the picture has been visible during the current trial. Thus the memory score is maximized by viewing the picture only briefly. The memory score is calculated only in trials where the subject manually shows and hides the picture. There is a forced delay (typical value 2s) after each time the picture shown, which imposes a fixed penalty for each viewing (through the speed score) and requires the subject to hold the picture in memory. The picture is initially hidden, so the subject may predict the next picture in the sequence of trials to achieve a perfect memory score, at the cost of a low accuracy score if the prediction is incorrect.
- **Overall:** the overall score s_O combines the subscores $S = \{s_A, s_S, s_M\}$, each with a corresponding weight $0 \leq \alpha_i \leq 1$ in Equation 3. Thus renders the corresponding metric entirely moot, while $\alpha_i = 1$ implies that the overall score cannot be higher than the subscore.

$$s_O \equiv \prod_i (1 - \alpha_i + \alpha_i S_i) \quad (3)$$

If required by the experiment design, visual feedback is presented by displaying the composite and overall scores graphically and numerically (**Fig. 2**). Below the overall score is a graph which shows proceeding trial scores, which may help a subject identify performance trends and motivate him or her to improve over time. The score display is updated at 10hz.

Significantly, the user interface does not display the system parameters (e.g. speed score half-life, nor subscore weights). For a good score, a subject must develop a strategy that is both consistent with their abilities, and which is rewarded by the environment at the time.

5.4 Task Manipulations

The drawing software supports several task manipulations to elicit strategy shift between and within subjects, including:

- **Picture:** The picture being drawn may be familiar or novel, detailed or simple, sharp-cornered vs. smooth, etc.
- **Affine Transformation:** The position, scale, and orientation of the Picture and Drawing areas can be set independently, forcing the subject to mentally transform the picture.
- **Drawing vs. Tracing:** The Picture and Drawing areas may coincide, resulting in a tracing task.
- **Memory:** The picture may be hidden and a delay imposed before drawing, forcing the subject to draw from memory.
- **Timeout:** Drawing time may be limited. The timeout is a normally distributed random variable invisible to the subject. This condition prompts the subject to choose between reliably earning a lower score by drawing quickly, or drawing more

slowly in hopes of a higher score at the risk of receiving no credit if the timeout is exceeded.

- **Interstimulus Interval:** The delay between trials is varied.
- **Background:** The backgrounds displayed in the Picture Area and Drawing Area (e.g. a grid) can be used to vary landmarks for the drawing task.
- **Invisible Drawing:** The marks drawn by the pen may be hidden (as if the pen were out of ink). This requires the subject to remember which parts of a figure have been completed and makes it harder to identify errors, decreasing the accuracy score.

5.5 Output

For each trial, the drawing task software outputs the following information:

- Each point in the picture
- Each point drawn by the subject, with time stamps. The sample rate averages 140 Hz which is limited by the windowing system (X.Org X Server 1.5.2 on Ubuntu Linux 8.10).
- All of the settings in effect during the trial
- The duration of the trial and the scores displayed to the subject.

6 Conclusion

This paper proposed that cognitive adaptability is a trait necessary to explain the inherently dynamic nature of cognitive processes as individuals adapt their available resources to ongoing circumstances. We outlined a research plan that is intended to establish cognitive adaptability by measurement and prediction of behavioral data and the discovery of neural correlates. Subsequent papers will document experiments and findings from this course of research.

References

1. Anderson, J.R., Lebiere, C.: The atomic components of thought. Erlbaum, Mahwah (1998)
2. Cooper, C.: Individual Differences. Arnold, Belfast (2002)
3. Miller, M.B., Van Horn, J.D., Wolford, G.L., Handy, T.C., Valsangkar-Smyth, M., Inati, S., Grafton, S., Gazzaniga, M.S.: Extensive individual differences in brain activations associated with episodic retrieval are reliable over time. *Journal of Cognitive Neuroscience* 148, 1200–1214 (2002)
4. Taylor, S.F., Welsh, R.C., Wager, T.D., Luan Phan, K., Fitzgerald, K.D., Gehring, W.J.: A functional neuroimaging study of motivation and executive function. *NeuroImage* 21(3), 1045–1054 (2004)
5. Wray, R.E., Laird, J.E.: An architectural approach to consistency in hierarchical execution. *Journal of Artificial Intelligence Research* 19, 355–398 (2003)