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Modeling the Relationship between Strategies, Abilities and Skilled Performance

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Abstract

Adoption of efficient strategies and tactics in performing tasks can have a profound impact on performance. The present research aimed to incorporate strategies and tactics into traditional models of skill acquisition, focusing on ability-performance relationships and the learning curve. The study involved 116 participants completing a series of ability tests (general, perceptual speed and psychomotor) and performing 54 trials on a text editing task. For each trial, speed, accuracy and strategy use were logged. Results showed that both abilities and adoption of superior strategies made unique contributions to predicting performance and that strategy partially mediated the ability-performance relationship. Performance and strategy use improved over time with strategy use in later trials making an incremental prediction on later trial performance over and above that of early trial performance. Results went against theories predicting changes in ability-performance correlations over time. Implications for the development of cognitive architectures are also explored.

Introduction

Everyday, in work and non-work settings, people perform tasks. People drive cars, prepare food, use computers, learn new skills, and engage in a series of activities involving various forms of skilled behavior. At an abstract level the very nature of cognition can be seen as goal directed information processing behavior involving the performance of tasks. Within most tasks, substantial differences exist between individuals on their level of performance as defined by such measures as speed and quality. Underlying such differences in task performance are differences in the methods and strategies of task execution. When driving home in peak hour, some people will be better able to predict the fastest route; when arranging the dishwasher, some people will arrange the dishes in a way that will speed up the loading and unloading; when preparing a Power Point presentation, some people will have tricks to automate the formatting of slides. Strategies are inextricably linked with human daily functioning and have substantial implications for individual, organizational and national efficiency.

Despite just over 100 years of research on skill acquisition (see Bryan & Harter, 1899) and human performance, strategies and other process variables, such as motivation and task mental models, have been relatively neglected within the skill acquisition literature (see eg., Langan-Fox, Armstrong, Balvin, Anglim, 2002 for a description). Over this time researchers have, among other things, attempted to model the learning curve (e.g., Newell & Rosenbloom, 1981), examine the relationship between abilities and performance (e.g., Ackerman, 1988), explore patterns of inter-trial correlations (e.g., Jones, 1970) , and develop cognitive architectures that simulate human information processing (e.g., Anderson, 1982; Newel, 1990). These modeling issues reflect fundamental questions about the nature of learning and how learning relates to human cognitive processes and abilities. However, across each of these modeling issues, there is a need to better integrate an understanding of the role of strategy in order to develop a more comprehensive theory of skill acquisition.

The focus of the present research is on integrating strategy into the important theoretical frameworks established within the human performance and skill acquisition field. Some initial work has already been conducted to examine the relationship between strategies and learning curves (Delaney, Reder, Staszewski, & Ritter, 1998), ability-performance relationships (Keil & Cortina, 1999) and cognitive architectures (John & Lallement, 1997). The present research aimed to develop these areas further by measuring within the one study, abilities, strategic orientation, task performance and strategy use over time. By obtaining such rich data and using modern analytic techniques, these traditional skill acquisition issues can be enriched by the incorporation of strategy as a key variable allowing new connections to be made.

Strategy and ability performance relationships

The issue of predicting performance on tasks from abilities has been a popular and contentious topic in psychology. Proctor and Dutta (1995) note that one concept common in this area, although not undisputed, is that the importance of particular abilities varies based on the demands of the task. This was first extensively assessed by Fleishman (1972) who proposed that as task demands change as a skill is acquired from high demands on cognitive resources to automated behavior, so would the relationships between abilities and performance. The basic design of Fleishman's studies was to administer a battery of ability tests and then record performance on a criterion task over several trials and examine the pattern of ability-performance correlations over time. Ackerman (1988) further refined a theory of ability performance correlations suggesting that general, perceptual speed and psychomotor abilities would have differential prediction as a skill was acquired. However, while individual differences in abilities are important in predicting performance, differences in strategy use

frequently account for even greater variability in performance.

Performing a re-analysis of Ackerman's (1988) performance data, Lee, Anderson and Matessa (1995) showed that strategy use accounted for 87.7% of variance in task performance. They suggested that performance increases were the result of both strategy improvements and increased speed with which particular strategies were executed. Any model of learning needs to incorporate both speed of execution and strategy shifts. However, Lee et al did not go on to report the relationship between strategy usage, performance and the ability measures used by Ackerman to measure performance.

From the analysis of this data Lee, Anderson, and Matessa (1995) drew several conclusions regarding strategy use: strategies reflect bounded rationality; individuals frequently changed strategies but rarely regressed to an inferior strategy; shifts were either gradual or abrupt; performance was predicted by knowledge of a superior strategy rather than the total number of strategies known; While the movement towards automaticity as typified by increases in speed of execution is important for improving performance, strategy use was also important.

Importantly for the present research, Lee, Anderson, and Matessa (1995) highlighted the utility of extracting strategy use from key log data on computer-based tasks. This approach allowed for the trial-by-trial monitoring of strategy usage and strategy shifts over time. This research also showed the importance of expanding research into individual differences in task performance to include differences in methods of task execution.

Thus it can be asserted that: first, strategies for performing tasks are an important consideration when understanding ability-performance relations; second, strategy use typically accounts for a substantial proportion of variance depending on the task and how strategy is defined; third, different strategies are likely to place different demands on abilities and therefore change the properties of the task; and fourth, people with different abilities are likely to perform tasks in different ways.

Hypotheses

Based on the previous research the following hypotheses were formulated:
1) Strategies and abilities would both make unique contributions in predicting performance.
2) Strategy use would partially mediate the relationship between abilities and performance.
3) Performance, accuracy and response time would improve over time with progressively smaller improvements with practice.
4) Use of measured strategies would be associated with faster performance.
5) Adoption of measured strategies would increase over time.

6) Strategy use in later trials would lead to incremental prediction of performance in later trials over and beyond earlier trial performance

Method

A sample of 116 participants performed the experiment. Median age was 23 and contained 60.3% females, 29.7% males. Due to issues of cheating, task non-completion and software errors, 99 participants were included in final analyses of strategy use.

For each ability construct three tests were selected in order to obtain a valid measure of each. General, perceptual speed and psychomotor ability tests were selected because of proven factor loadings in past studies (Armstrong and Langan-Fox, 2000). Selected tests also corresponded to appropriate points on the speed-level dimension that Ackerman (1988) extracted from a multidimensional scaling of 31 reference test variables from Allison's (1960) data.

To measure general ability, the Extended Range Vocabulary, Inference and Cube Comparison Tests were used (Ekstrom et al 1976). To measure perceptual speed ability the Number Comparison, Number Sort (Ekstrom et al 1976) and Clerical Speed and Accuracy tests (Bennet et al 1972) were used. Finally, to measure psychomotor ability, Simple, 2-Choice and 4-Choice reaction time tests were used (Anglim, 2000).

The primary performance task was derived from a study by Armstrong and Langan-Fox (2000) examining participants' ability to acquire the skill of repeatedly editing a passage of text. While the present task resembles that used by Armstrong and Langan-Fox, the length of the text passage was reduced to allow for a greater number of trials to be completed. Additionally, real world text-editing keys were used that allow for more advanced cut, paste and selections operations. These keys include pressing shift and a cursor to navigate the cursor between words instead of one character at a time. Such short-cut keys allow for greater variation in production strategies. The passage of text chosen included three long sentences and seven broad corrections. These involved deleting words, cutting and pasting words, selecting passages of text, and inserting new characters.

The text editing task involved one practice trial with no time limit followed by three sets of 18 trials, which amounted to a total of 54 performance trials. If the participant did not complete the trial after 60 seconds, the trial would end automatically. This ensured that all participants completed the 54 trials in the required amount of time.

Results

For each trial five strategy variables were created. First, raw key log files containing the sequence and timings of key presses were imported into a database. From this database, particular key combinations were extracted based on their ability to identify potentially superior text editing strategies. These strategies will be hereafter referred to by their number

as: 1) control & cursor – move cursor between words; 2) control & shift & cursor – select word at a time; 3) home and/or end keys – navigate directly to start end of line; 4) typing versus cut paste strategy; and, 5) shift delete – deletes entire word. An aggregate strategy use variable was created by getting a total number of strategies used for the trial.

Accuracy data was rated out of 12 based on the number of correct changes that were made in the text. The measure of accuracy was combined with trial response time (RT) to create a variable that represented trial performance. This measure of performance aimed to estimate the time it would have taken a participant to complete the trial with complete accuracy. The procedure for deriving the weights was based on an optimal scaling procedure previously used by Azjen (1991). For the purpose of assessing overall performance and smoothing out random variation between trials, trial performance measures and response times were aggregated into three blocks (trials 1 to 18, 19 to 36, 37 to 54) based on a simple average.

Strategy Use and the learning Curve

Table 1 shows that based on t-tests significant differences were observed (p<.01) in mean response time for four out of the five strategies, supporting the idea that they were more efficient.

Table 1: Mean trial completion times (seconds) based on strategy use averaged over three time segments (trials 1-18; 19-36; and 37-54).

Strategy Number	S1*	S2*	S3*	S4	S5*
Strategy Used (mean RT)	31.5	33.8	32.8	33.4	23.4
Strategy Not Used (mean RT)	39.9	38.7	39.4	37.0	37.4
Percentage Used (%)	43	49	48	23	9

sd =11.0, n = 99, *p < .01

Figure 1 shows the progressive improvement over time in average levels of performance (a measure of speed adjusted for accuracy), speed and accuracy. It also shows that improvements between trials were smaller over the course of practice to the point at the end of practice where performance appeared to have leveled off. Finally, it shows that the adoption of strategies increased consistently over time from a mean of 1.0 strategies out of 5 at trial 1 to 1.9 strategies by trial 54.

Table 2 reports the individual regression weights for a multiple regression looking at strategy and ability variables predicting text editing response time. The model accounted for a significant amount of variance, $R^2 = .60$, F (8, 88) = 16.5, p < .001. Three of the five strategies had significant Beta weights predicting faster performance. The zero-order column shows the raw correlation between the predictors and response time highlighting that the presence of all

strategies (note that strategy 4 is not significant) and the increase in abilities is associated with reduced response times.
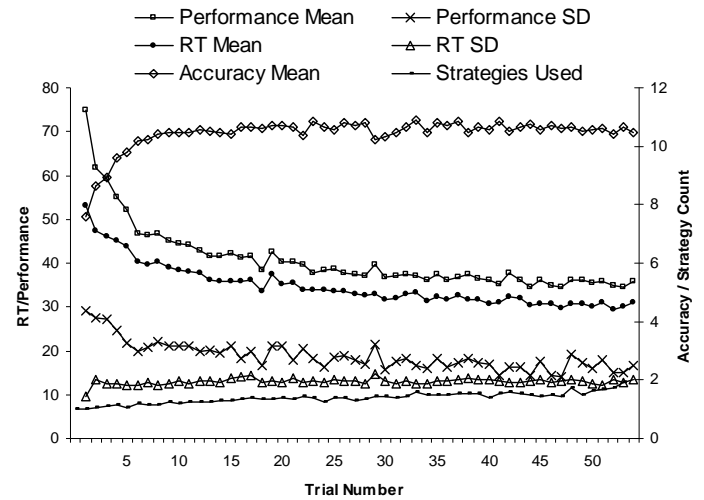

Figure 1. Graph of mean and standard deviation performance and response time and mean accuracy over time.

Table 2: Multiple regression of strategies and abilities predicting mean response time for trials 37-54.

Variable	Beta	Zero-order	Semi-partial
DV: Average RT Trials 37-54			
Strategy 1	-.16*	-.42	-.13
Strategy 2	-.08	-.32	-.07
Strategy 3	-.21**	-.41	-.20
Strategy 4	-.09	-.11	-.09
Strategy 5	-.23**	-.39	-.21
Psychomotor	-.30**	-.64	-.23
Perceptual Speed	-.17*	-.43	-.15
General	-.14	-.36	-.12

Note: * p < .05, **p < .01

To examine whether later phase strategy use led to incremental prediction on performance over earlier trials a hierarchical regression was performed placing text editing performance for time 3 as the dependent variable and time 1 as the predictor in the first step. Strategy use at time 3 was added in the second step. Results showed a significant increase in prediction when strategy use at time 3 was added to the model, R^2 change = .04, F (1, 95) = 21.1, p<.001 (see Table 3). In contrast there was no significant incremental prediction of time 3 performance by the three abilities over and beyond time 1 performance, R^2 change = .01, F(3, 92) = 2.1, *ns*.

Table 3: Multiple regression of strategies and abilities predicting mean response time for trials 37-54.

Variable	Beta
DV: Text Edit Performance Time 3	
Step1	
Text Editing Performance Time 1	.88***
Step 2	
Text Editing Performance Time 1	.76***
Strategy Use Time 3	-.23***

Note: R^2 for step 1 = .78, ΔR^2 = .04 for step 2 (p < .001); ***p < .001

Structural Equation Modeling

Structural Equation Modeling allows for the modeling of correlations between a set of variables in a more integrated way than traditional multivariate procedures. It allows for the examination of mediational hypotheses, assessment of measurement models and comparison of competing theoretical models. In the present experiment structural equation modeling allows for the examination of the potential mediating role of strategy between abilities and task performance. It also allows for examination of whether the effect of abilities and strategies on later performance is mediated by initial performance.

An initial confirmatory factor analysis was performed to examine the measurement model of the three abilities. Tests did tend to cluster well under the three hypothesized abilities with the exception of one test that had some dual loadings on general and perceptual speed ability.

A path diagram of the structural equation model of the ability, strategy and task performance data is presented in Figure 2. The three abilities were theorized to be correlated and predict both performance and strategy use. Strategy use was expected to be a direct predictor of performance, but also partially mediate the relationship between abilities and performance. Performance and strategy use at time one was hypothesized to mediate the influence of abilities on time two and time three. Strategy use at later phases was predicted to have additive predictive value on performance over and above prior performance.

A Generalized Least Squares estimation procedure was used, because Maximum Likelihood resulted in estimation problems. It should be noted that the sample size used for the analyses is on the low end for performing structural equation modeling, which may mean among other things that the model is less replicable and that the chi-square test is more optimistic regarding model fit. Model Fit statistics show that the model provided a reasonable fit for the data, Chi-Square (df = 80, n = 97) = 105.0, p = .03, RMSEA = .057 (lower=0.18, higher = .085), GFI=.854. To guide interpretation of the above values the following rules of thumb may be used. An RMSEA below .05 is considered very good fit, and below .08 reasonable, a GFI above .90 is preferable, and holding sample size constant a less significant chi-square is desirable.

However, it should be noted that the chi-square test is stringent testing for exact congruence between model and sample covariance matrices, and that typically the RMSEA provides a better guide to whether the model is a good representation of the data. An examination of the standardized covariance residuals showed that the measurement model for the ability tests could be slightly refined.

Table 4: Correlation matrix of abilities, strategy use, accuracy and performance.

	SD	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1 ST1: Strategy Use Time 1	(1.6)														
2 TEP1: Task Performance Time 1	(18.1)	-.51													
3 ST2: Strategy Use Time 2	(1.8)	.89	-.48												
4 TEP2: Task Performance Time 2	(15.8)	-.59	.93	-.54											
5 ST3: Strategy Use Time 3	(1.8)	.81	-.51	.93	-.56										
6 TEP3: Task Performance Time 3	(14.4)	-.64	.89	-.62	.95	-.62									
7 PSS: Perceptual Speed – Sort Test	(1.0)	.29	-.42	.27	-.41	.27	-.37								
8 PSC: Perceptual Speed – Comparison	(1.0)	.15	-.26	.12	-.27	.11	-.27	.63							
9 PSCL: Perceptual Speed – Clerical	(1.0)	.30	-.41	.30	-.45	.29	-.46	.52	.46						
10 GC: General Ability – Cube Test	(1.0)	.18	-.36	.13	-.35	.15	-.32	.21	.29	.26					
11 GI: General Ability – Inference	(1.0)	.24	-.29	.19	-.30	.23	-.32	.36	.42	.13	.33				
12 GV: General Ability – Vocabulary	(1.0)	.17	-.15	.19	-.15	.18	-.21	.25	.17	-.03	.10	.61			
13 PMS: Psychomotor – Simple	(0.9)	.31	-.56	.31	-.57	.39	-.53	.29	.29	.36	.20	.28	.07		
14 PM2: Psychomotor – 2 Choice	(0.9)	.48	-.55	.49	-.59	.55	-.59	.32	.32	.42	.15	.24	.06	.72	
15 PM4: Psychomotor – 4 Choice	(0.9)	.48	-.58	.50	-.62	.54	-.59	.30	.23	.41	.24	.24	-.01	.67	.84

Note: correlations greater than ±.17 are significant at p<.05 (2-tailed) and correlations ±.26 are significant at p<.01 (2-tailed).
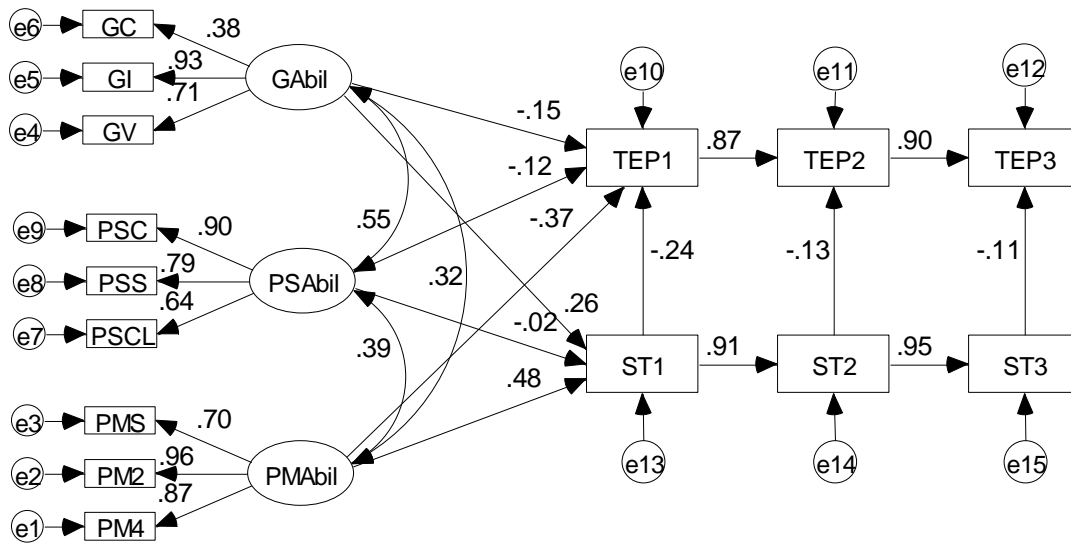
Note: Numbers represent standardized regression weights. GAbil: General Ability; PSAbil: Perceptual Speed Ability; PMAbil: Psychomotor Ability; ST1 to 3: Strategy at time 1 to 3; TEP1 to 3: Text Editing Performance at time 1 to 3.
Figure 2: Structural equation model of ability, strategy and performance variables.

Table 4 shows the raw correlation matrix which when in the form of a covariance matrix formed the basis of the structural equation model. It can be seen that individual differences in text editing performance and strategy use was fairly stable over time. Correlations between time points are larger when they are adjacent than between time point 1 and 3. Correlations between tests measuring abilities generally reflected the idea that they were measuring unique constructs. Each set of tests had relatively high internal correlations between tests with the exception of the cube comparison test which had relatively low correlations with other general ability tests.

Discussion

The results showed that on the text editing task both abilities and strategy use were important predictors of task performance. All three ability constructs were related but had differential prediction of text editing performance and strategy use. In particular psychomotor ability was the strongest predictor of text editing performance and strategy use.

The particular pattern of prediction of abilities is likely due to the nature of the task, which requires quick responses on a computer. The task is also one where clear behavioral based tactics can be specified and logged enabling strategy use to be a substantial predictor.

Performance in terms of both speed and accuracy improved over the course of practice. The pattern of improvement was consistent with most skill acquisition studies showing progressively smaller improvements over time reaching an asymptote. Use of superior strategies also increased over time. It is likely that performance improvements resulted from a combination of the use of more efficient strategies and smoother, more rapid execution of particular techniques. The structural equation model supported the idea that future performance is best predicted by past performance. The influence of abilities on performance on later trials was mediated by performance on earlier trials. Thus, there was no support for claims for incremental increases in prediction of psychomotor ability as set out by Ackerman (1988). In contrast strategy use in later trials did lead to incremental prediction of later trial performance over and above that predicted by performance in earlier trials.

While it was clear that learning occurred on the task as indicated by improvements in performance and strategy use, individual differences remained quite stable between blocks of time. Thus, people's relative performance ranking did not change substantially over time. Because of this, there is little scope for changes in ability-performance relationships over time. In this case a mediational relationship is more meaningful whereby the effect of external variables such as ability on later performance are accounted for by earlier performance.

The particular pattern of performance correlations and strategy correlations over time was consistent with the notion of emergent change phenomena. This notion suggests that correlations will be larger if the two time points are closer in time. This is because changes emerge out of the past state. Such an effect is likely to be stronger when aggregate time points are considered, because they are more reliable estimators of task performance than individual trials which can be more influenced by random factors.

Results also have implications for the development of cognitive architectures.

Implications for Cognitive Architectures

The present research aimed to highlight the importance in incorporating individual differences both in terms of within person differences (ability, motivation, etc.) and within task

differences (strategy) into cognitive architectures. It is important to incorporate the differences between individuals and the process by which strategies change over time. These are likely to be related and depend on the task for their interactions.

Several researchers have started to look at developing models of learning that incorporate strategy shift over time and how this interacts with performance. Simon and Halford (1995) developed a model of strategy selection, where strategies were selected based on strength of strategy. Schunn has suggested that more research needs to be done to answer the questions relating to the nature and causes of strategy shifts and strategy adoption and that computational modeling using ACT-R (Schunn & Anderson, 1998) and other architectures such as Reder's SAC (Source Activation Confusion) model (Reder & Schunn, 1996) will help explain these processes.

In terms of incorporating abilities and traits into models of learning, Taatgen (2001) has attempted to develop an ACT-R simulation of the Kanfer-Ackerman's Air-Traffic Control Task that incorporated the individual difference measures of ability in the study. Hudlicka (2002) has also developed a symbolic cognitive architecture that incorporated personality characteristics (traits) and transient emotions (states) as parameters that influence agent behavior.

One argument made here is that the two modeling issues of strategy shift and ability-performance relationships are related. One of the ways abilities can predict performance is that people who are higher on abilities are able to apply and learn superior strategies. Thus, collecting data from human participants provides a test for the effectiveness of cognitive simulations attempt to model such processes.

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