Special Section

Contrasting Acquisition-Focused and Performance-Focused Models of Acquired Behavior

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Abstract

What is encoded during a learning experience? In a learning situation, a training (acquisition) phase is often followed by a test phase. Acquisition-focused models (most associative models) emphasize information processing that occurs during training and assume that only summary statistics (associative values) are retained to influence behavior during testing. Performance-focused models (a k a "computational" models) emphasize information processing that occurs at test and often assume fairly comprehensive memory of prior experiences. In this article, we contrast these two families of models. We note that neither family can claim unique support from the various learning phenomena commonly cited as favoring one or the other position. Within each family, there are highly diverse models that preclude blanket generalizations. However, the acquisition-focused view that subjects retain only summary statistics suggests unrealistically impoverished memories relative to the fairly veridical memories that clearly are formed. But this oversimplifying assumption of acquisition-focused associative theories is exactly what has made them superior to performance-focused models to date in stimulating research.

Keywords

acquisition-focused models; performance-focused models; associations; computational models

Stimulus-specific changes in behavior as a function of experience (learning) are central to how people adapt to environmental contingencies. To better understand the nature of learning, psychologists ask, what is the content of information retained between training and testing? Models attempting to account for learning fall into two families, those that focus on mental processes occurring during training (acquisition) and those that focus on mental processes occurring during testing (performance). These two families of models differ greatly in their views concerning what organisms encode and whether behavior is an accurate indicator of what was encoded.

Acquisition-focused models assume that when two stimuli (e.g., a cue and an outcome) are paired, an association between their mental representations is established; the value of the association is weighted in favor of recent events as a result of its being frequently updated by the subject. No memories of specific prior events nor past associative values are assumed to be retained after updating; rather, relationships between events (stimuli or responses) are encoded exclusively as *summary statistics*. (These summary statistics are usually associative strengths, but need not be; Pearce & Hall, 1980). Thus, acquisition-focused models are impoverished with respect to specific details from the past, and assume that subjects lack memories of specific past events. Responding to cues is presumably dependent on current values of cue-outcome associations.

In contrast, performance-focused models of learning assume experiences are encoded more veridically and that, at test, responding is based on processing of part of this information. For example, Rescorla's (1968) contingency model assumes that acquired responding results from computation based on the frequencies of four trial types: (a) cue and outcome present, (b) cue and outcome absent (these first two types favor responding to the cue), (c) cue-only present, and (d) outcome-only present (these latter two types oppose responding). Thus, the subject presumably retains the frequency with which each of the four trial types has occurred. (Calling such models computational is misleading because all quantitative models, acquisition- and performance-focused alike, involve computation; performance-focused models are also sometimes called rule-based, contingency, or statistical models.) Thus, performance-focused models assume that there are memories of specific past events (rather than merely summary statistics), and consequently a large potential store of latent memories. These models anticipate extensive information processing on each training trial because on each trial (training or test) a decision must be made whether to respond. However, in performance-focused models, the trial-by-trial processing that regulates responding applies only to immediate behavior. The only effect of processing during a trial that will influence performance on subsequent trials is storage of a record of events (including re-

sponding) that occurred on that trial.

The distinction between these two families of models is important because they anticipate great differences in the latent content of memory. For example, consider how these models might explain the distortion of eyewitness testimony as a result of leading questions being asked following training (witnessing an event and being questioned about it subsequently can be regarded as forms of training and posttraining treatment, respectively). Does such distortion reflect permanent loss of the original memory (as suggested by acquisition-focused models, which assume that new training in the form of a memory-distorting leading question irreversibly modifies the memory of original training) or merely a decrement in accessibility (as suggested by performance-focused models)?

Notably, some performance-focused models speak of associations, but still emphasize information processing at test. For example, our comparator hypothesis explains many behavioral phenomena on the basis of comparisons that occur at test between different associations acquired during training as a result of simple contiguity (i.e., processing during training is simpler than in most acquisition-focused models, in which associations are acquired on the basis of additional factors such as nonredundant information value; Miller & Matzel, 1988; also see Denniston, Savastano, & Miller, 2001). Similarly, Bouton (1993) explained numerous phenomena in terms of competition for retrieval at test between different simply acquired associations. We regard these two models as performance-focused despite their use of associations because they assume that the critical processes (i.e., comparisons and selective retrieval) occur at test, and they both require more extensive memory than traditional associative models to retain the memories that are compared or compete for retrieval. Table 1 lists some representative acquisition- and performance-focused models.

Advocates of performance-focused models (e.g., Gallistel & Gibbon, 2000) have claimed that there are fatal flaws in the entire family of acquisition-focused models, and vice versa (Allan, 1993). Often these strong conclusions come from assessment of a single model, and are then generalized to other models within its family. In this article, we review some of the phenomena that advocates of one family of models have used as the basis of arguments for rejecting the other family.

SOME DECISION PHENOMENA THAT ARE NOT DECISIVE

Timed Responding by Subjects

Gallistel and Gibbon (2000) recently proposed rate-expectancy theory (RET), an intriguing performance-focused model that readily

Table 1. *Some representative models of simple acquired behavior*

Acquisition-focused models	Performance-focused models
Bush & Mostellar (1955): a pure contiguity model that focuses on processing of the representation of outcomes. It accounts for some trial-order effects, but not for cue competition.	Rescorla's (1968) contingency model: a model that hinges on the relative frequency of cue-outcome, cue-alone, outcome-alone, and no-cue/no-outcome trials. It cannot account for cue competition or trial-order effects.
Rescorla & Wagner (1972): a model that focuses on processing of the representation of outcomes and can account for trial-order effects and cue competition.	Cheng & Novick's (1991) focal-set model: similar to Rescorla's (1968) contingency model, but with selection rules for which trials to consider that allow it to account for cue competition. It cannot account for trial-order effects.
Mackintosh (1975): a model that focuses on processing of representations of cues and can account for trial-order effects and cue competition.	Miller & Matzel's (1988) comparator hypothesis: a model that focuses on the degree to which a cue predicts increases or decreases in the likelihood of the outcome relative to the background of training. It accounts for cue competition but not trial-order effects.
Wagner's (1981) SOP model: a complex real-time model that can account for trial-order effects and cue competition.	Bouton's (1993) retrieval model: emphasizes the importance of the specific cues present at test. It accounts for trial-order effects but not cue competition.
All connectionist models (e.g., Quinlan, 1991): characterized by their use of large numbers of associations.	Gallistel & Gibbon's (2000) rate-expectancy theory: a real-time model that focuses on the degree to which a cue predicts increases or decreases in the likelihood of the outcome relative to the context. It accounts for cue competition and trial-order effects.

accounts for how animals distribute their behavior in time, an aspect of acquired behavior notably neglected by acquisition-focused models that view learning events in terms of separable trials (e.g., Rescorla & Wagner, 1972). However, RET's success with response timing originates in its being a real-time model, not in its being a performance-focused model. (In real-time models, summary statistics are updated continuously, rather than only at the end of a trial.) Performance-focused models need not be real time. In fact, most performance-focused models are not. Moreover, there are several real-time acquisition-focused models (Wagner, 1981). Therefore, the real-time aspect of RET is neither unique to, nor characteristic of, performance-focused models. Nor is the real-time aspect entirely commendable; real-time models must pay a great price in terms of increased complexity.

Rate of Acquisition

Allan (1993) faulted performance-focused models for not accounting for the fact that acquisition of a learned behavior is ordinarily gradual (over trials). Surely, Rescorla's (1968) performance-focused contingency model fails to account for this because it assumes responding is sensitive to percentages of different trial types. Thus, learning should be maximal after one trial if that trial is a cue-outcome pairing. In contrast, all contemporary acquisition-focused models anticipate gradual acquisition (the old all-or-none models are out of fashion). However, the performance-focused RET predicts gradual learning curves because (a) its statistical response rule is sensitive to the number of signal-outcome pairings (just as *F* tests are sensitive to sample size), and (b) the increasing nonreinforced time in the training context over trials decreases the degree to which the reinforcement is attributed to the context alone. Thus, gradual acquisition is not uniquely predicted by either family of models.

Cue Competition

Early performance-focused models could not account for cue competition (e.g., *blocking* in which the presence of a previously trained, blocking, cue during training of a new, blocked, cue interferes with the new cue coming to elicit responding). Indeed, this was one reason for Rescorla's abandoning his 1968 contingency model in favor of an acquisition-focused model (Rescorla & Wagner, 1972). However, the performance-focused comparator hypothesis (Miller & Matzel, 1988) also accounts for cue competition. Specifically, according to this hypothesis, responding to a cue at test depends not only directly on the cue-outcome association, but also inversely on associations between the target cue and competing cue and between the competing cue and the outcome. Additionally, Cheng and Novick (1991) and Gallistel and Gibbon (2000) have provided alternative performance-focused accounts of blocking. Moreover, the model from which the Rescorla-Wagner model evolved, Bush and Mostellar (1955), was an acquisition-focused model that did not account for blocking. Thus, a focus on acquisition is neither necessary nor sufficient to account for cue competition.

Trial-Order Effects

The performance-focused comparator hypothesis anticipates blocking regardless of whether the blocking cue is reinforced alone before or after it is reinforced in compound with the blocked cue (forward or backward blocking, respectively). In contrast, Rescorla and Wagner's (1972) model anticipates only forward blocking. The fact that many animal studies have demonstrated forward blocking but clearly demonstrating backward blocking in animals has been difficult (a trial-order effect) is problematic for the comparator hypothesis, and, by (over)generalization, is sometimes viewed as problematic for all performance-focused models. Conversely, the frequent observation of backward blocking in humans, when a causal attribution task with blocking and blocked causes is substituted for the conventional Pavlovian blocking task that is used with animals, is problematic for Rescorla and Wagner, and, by (over)generalization, is sometimes viewed as problematic for all acquisition-focused models. The actual occurrence of backward blocking depends on details of the learning task (Miller & Matute, 1996). Some of the newest acquisition-focused models (e.g., Van Hamme & Wasserman, 1994) actually predict backward blocking, as do most performance-focused models.

More generally, most performance-focused models treat all relevant prior events as equal regardless of their recency, whereas acquisition-focused associative theories, by virtue of their frequent updating of summary statistics, favor recent events. Surely, trial-order effects are observed in many (but not all) situations. For example, given many cue-outcome pairings followed by many cue-alone (extinction) presentations, subjects will not respond. In contrast, if the nonreinforced presentations precede the reinforced ones, after all the reinforced trials subjects will respond. Such trial-order effects have been cited as problematic for performance-focused models in general. However, although performance-focused models assume an accumulation of large amounts

of information, these models can account for trial-order effects by using a weighting factor that discounts less recent events. Gallistel and Gibbon's (2000) RET effectively does exactly this. Hence, trial-order effects do not demand rejection of performance-focused models en masse.

Path Dependence

Path dependence refers to different behaviors resulting from identical treatment of subjects who at the start of treatment exhibited the same behavior but had different conditioning histories. For example, consider spontaneous recovery of Pavlovian responding following extinction. Subjects that have completed extinction treatment (extinguished subjects) behave identically to naive subjects in not responding to the cue. But if testing is delayed, responding is again observed in the extinguished subjects. Spontaneous recovery, as this phenomenon is called, is anticipated by most performance-focused models (e.g., Rescorla, 1968) because cue-alone (extinction) trials are assumed not to erase memories of the cue-outcome pairings. Retention intervals are effectively a series of trials with both cue and outcome absent, and such trials favor responding to the cue because they enhance the cue-outcome contingency. In contrast, spontaneous recovery is problematic for most contemporary acquisition-focused associative theories (e.g., Rescorla & Wagner, 1972), and acquisition-focused models in general have been faulted for not accounting for path dependency. But spontaneous recovery can be accommodated by acquisition-focused associative theories if extinction is conceptualized as arising from new inhibitory learning rather than unlearning of excitatory associations (e.g., Wagner, 1981), *and* if inhibition is assumed to wane faster than excitation over retention intervals. Thus, spontaneous recovery from extinction is problematic not for acquisition-focused models in general, but only for specific ones.

Memory Capacity

A frequent objection to performance-focused models is that they are extravagant in their use of memory; subjects are assumed to remember large numbers of specific experiences rather than just a relatively few summary statistics. However, there is little empirical basis for thinking that limited (long-term) memory capacity influences how acquired information is processed. Analyses of errors in categorization tasks indicate that subjects often compare new items with memories of many past items rather than with a single category prototype, a finding suggestive of enormous memory capacity. Similarly, subjects' ability to recognize vast numbers of pictures after a single hurried viewing of each suggests a large memory capacity.

CONCLUSIONS

Failure to account for any of the phenomena we have discussed is not an inherent characteristic of either family of models, but is specific to some models within each family. Experiments might be designed to contrast a specific acquisition-focused model with a specific performance-focused model, but the different models within each family are too heterogeneous to test en masse. Researchers have formulated new acquisition-focused (e.g., Van Hamme & Wasserman, 1994) and performance-focused (e.g., Denniston et al., 2001; Gallistel & Gibbon, 2000) models that account for data problematic for older acquisition-focused and performance-focused models. Thus, specific models of acquired behavior can be refuted, but the entire family of acquisition-focused or performance-focused models cannot be.

Although we have dichotomized models of acquired behavior into two families in order to contrast them, all models require some degree of information processing at both training and test. However, attempts to construct models that incorporate nontrivial processing at both times ordinarily result in theories that are too complex to generate unambiguous predictions. Thus, selectively emphasizing processing during acquisition or testing appears at this time a more useful strategy in stimulating research than does conforming to reality.

A good model stimulates research that results in the discovery of new relationships by making falsifiable predictions. Seemingly, the key to a model's generating falsifiable predictions is not whether it is acquisition- or performance-focused. Rather, the key is the model's simplicity. Models with many processes and parameters can be tweaked to account for most any observation, whereas simpler models are less ambiguous. As a result, simpler models are often proven wrong, but in the process, illuminating new phenomena are often observed. The models of Rescorla and Wagner (1972) and Rescorla (1968) are examples of simple acquisition- and performance-focused models, respectively, that proved erroneous in many respects, but were highly successful in stimulating research. In contrast, we fear the complexity of Gallistel and Gibbon's (2000) RET will limit its success as we have defined it.

One might contrast acquisition- and performance-focused models in terms of what is remembered. Consistent with the spirit of performance-focused models, introspec-

tion (as misleading as it can be) finds detailed memories of past events, and many of these memories can be confirmed as veridical. Thus, people's sense of remembering specific events is not illusionary. Performance-focused models assume that these memories guide behavior. Alternatively, people might retain summary statistics as well as memories of specific past events, but use only summary statistics to guide behavior. However, this would leave memories of specific events as useless artifacts (which they might well be . . .). But such a conclusion is implausible given what is known about natural selection. Although performance-focused models appear closer to reality, acquisition-focused associative models in recent years have been of greater heuristic value in stimulating research. This stems from researchers' underusing performance-focused models for historical reasons, and also from performance-focused models tending to be more complex than acquisition-focused models because of the greater information retained.

Recent efforts to better model how information is used at test have introduced mechanisms for conditional discriminations (occasion setting), clever use of retrieval cues, elaborated rules for the expression of knowledge, and associations that do more than simply link two representations (e.g., encode temporal relationships). We anticipate that in the future these improvements will better allow performance-focused models to generate testable predictions, thus permitting performance-focused models to join acquisition-focused models center stage in stimulating the discovery of new phenomena in basic learning and memory. Surely the richer memories assumed by performance-focused models have greater promise in illuminating the extent and accessibility of latent memories. The nature and manipulation of latent memories are apt to be a focus of future research because of their importance in applied situations such as eyewitness testimony.

SUMMARY

Acquired behavior obviously depends on both the acquisition of relationships in the environment and the expression of those relationships; ultimately, a comprehensive model will have to address both processes. But presently, simplified models that focus on one or the other process appear most likely to stimulate further research. Do acquisition- or performance-focused models of acquired behavior better describe how subjects process representations of contiguous events? This question cannot be answered for such broad classes of models. Meaningful comparisons are possible only between specific models. Models within both families continue to improve, quickly rendering global statements about entire families of models obsolete.

Recommended Reading

Allan, L.G. (1993). (See References)
Denniston, J.C., Savastano, H.I., & Miller, R.R. (2001). (See References)
Gallistel, C.R., & Gibbon, J. (2000). (See References)
Rescorla, R.A. (1968). (See References)
Rescorla, R.A., & Wagner, A.R. (1972). (See References)

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Note

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References

Allan, L.G. (1993). Human contingency judgments: Rule based or associative? *Psychological Bulletin*, *114*, 435–448.

Bouton, M.E. (1993). Context, time, and memory retrieval in the interference paradigms of Pavlovian learning. *Psychological Bulletin*, *114*, 80–99.

Bush, R.R., & Mostellar, F. (1955). *Stochastic models for learning*. New York: Wiley.

Cheng, P.W., & Novick, L.R. (1991). Causes versus enabling conditions. *Cognition*, *40*, 83–120.

Denniston, J.C., Savastano, H.I., & Miller, R.R. (2001). The extended comparator hypothesis: Learning by contiguity, responding by relative strength. In R.R. Mowrer & S.B. Klein (Eds.), *Handbook of contemporary learning theories* (pp. 65–117). Hillsdale, NJ: Erlbaum.

Gallistel, C.R., & Gibbon, J. (2000). Time, rate, and conditioning. *Psychological Review*, *107*, 219–275.

Mackintosh, N.J. (1975). A theory of attention: Variations in the associability of stimuli with reinforcement. *Psychological Review*, *82*, 276–298.

Miller, R.R., & Matute, H. (1996). Biological significance in forward and backward blocking. *Journal of Experimental Psychology: General*, *125*, 370–386.

Miller, R.R., & Matzel, L.D. (1988). The comparator hypothesis: A response rule for the expression of associations. In G.H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 22, pp. 51–92). San Diego: Academic Press.

Pearce, J.M., & Hall, G. (1980). A model for Pavlovian conditioning: Variations in the effectiveness of conditioned but not unconditioned stimuli. *Psychological Review*, *87*, 332–352.

Quinlan, P. (1991). *Connectionism and psychology*. Chicago: University of Chicago Press.

Rescorla, R.A. (1968). Probability of shock in the presence and absence of CS in fear conditioning. *Journal of Comparative and Physiological Psychology*, *66*, 1–5.

Rescorla, R.A., & Wagner, A.R. (1972). A theory of Pavlovian conditioning: Variations in the effectiveness of reinforcement and nonreinforcement. In A.H. Black & W.F. Prokasy (Eds.), *Classical conditioning II: Current research and theory* (pp. 64–99). New York: Appleton-Century-Crofts.

Van Hamme, L.J., & Wasserman, E.A. (1994). Cue competition in causality judgments: The role of nonpresentation of compound stimulus elements. *Learning and Motivation*, *25*, 127–151.

Wagner, A.R. (1981). SOP: A model of automatic memory processing in animal behavior. In N.E. Spear & R.R. Miller (Eds.), *Information processing in animals: Memory mechanisms* (pp. 5–47). Hillsdale, NJ: Erlbaum.