Induction of Continuous Stimulus-Response Relations

Proceedings of the Annual Meeting of the Cognitive Science Society, 11(0)

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1989

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ABSTRACT

The present research investigates the mental processes involved in inducing continuous stimulus-response relations. A simple perceptual-motor learning task was used in which subjects learned to produce a continuous variable (response duration) accurately for values chosen from another continuous dimension (stimulus length). Subjects were trained on several "practice" pairs, for which they received feedback about the correct responses. Trials involving practice pairs were intermixed with trials involving "transfer" pairs, for which no feedback was given. The correct responses and stimuli were related by simple mathematical functions: a power (Experiment 1); a logarithmic (Experiment 2); and a linear function with a positive intercept (Experiment 3). Experiment 1 demonstrated that people can learn a power function rapidly and use it to perform as well for transfer pairs as for practice pairs. Experiments 2 and 3 revealed a systematic pattern of bias during early learning, consistent with the hypothesis that people have a predisposition toward inducing a power function. However, the biases decreased in magnitude with practice.

We propose an account for induction of continuous stimulus-response relations called the "adaptive-regression" model. According to it, people are initially biased to induce a power function, but the bias is gradually weakened through experience, so that other stimulus-response relations can be learned with sufficient practice. The present results support the adaptive-regression model.

INTRODUCTION

A major objective in the study of learning is to describe inductive generalization (Holland, Holyoak, Nisbett, & Thagard, 1986). As part of achieving this objective, one must determine how associations between continuous stimulus and response variables that have an indefinitely large set of values are learned. Such learning underlies the development of many physical skills, including reaching, walking, and driving a car, which require accurate mappings of continuous stimulus variables (e.g., distance, size, and velocity) onto continuous response variables (e.g., force and duration). Consequently, interesting questions arise when the acquisition of these skills is viewed as a problem of inducing continuous stimulus-response relations on the basis of specific experiences. For example, how do people use prior experience with specific stimuli and associated responses to select responses to novel stimuli? Are certain types of stimulus-response relations more natural and learnable than others? We report results from three experiments designed to address these and other related questions in the domain of perceptual-motor learning.

EXPERIMENT 1

Overview

Experiment 1 was conducted over 5 sessions. During each session, there was a sequence of 60 trial blocks, in which learning and test trials were interspersed. On the learning trials, we presented subjects with practice stimuli chosen from a continuous stimulus dimension (length). For each practice stimulus, the subjects had to learn to produce a particular response chosen from another continuous response dimension (duration). Their performance was reinforced by giving feedback after each learning trial. The stimuli and associated correct responses were selected so that they were related by an underlying quantitative relation, namely, a power function. Our aim was to study whether subjects would discover and use this rule in making their responses to other transfer stimuli.

To achieve this aim, test trials were intermixed with learning trials. During test trials, the subjects had to produce responses for transfer stimuli whose magnitudes differed from those of the practice stimuli. No feedback about response accuracy was provided for the transfer stimuli. However, it was possible, in principle, for the subjects to produce appropriate responses to the transfer stimuli as well as the practice stimuli, if they successfully induced the underlying relation between the practice stimuli and responses.

Method

Design. Six University of Michigan students participated as subjects. The power function that they had to learn was specified by 12 stimulus-response pairs, as shown in Table 1. These pairs were generated with the equation $D = 257.24\ L^{.33}$, where L and D denote stimulus length (in mm) and response duration (in msec), respectively. Four of the 12 stimulus-response pairs (Pairs 5 through 8) served as transfer pairs, and the remaining 8 served as practice pairs. Each stimulus was presented once per block. The order of stimuli within each block was randomized.

Procedure. At the beginning of each trial, a display containing two vertical bars appeared on a display screen. The two bars were centered on the screen, and were separated by a variable stimulus length. The subjects' task was to produce a response duration that correctly matched the stimulus length, as specified by the underlying stimulus-response relation (i.e., power function). Subjects initiated the response duration by pressing a key and terminated the duration by pressing the same key a second time.

Table 1. The Stimulus-Response Pairs in Experiment 1

Pair	1	2	3	4	5	6	7	8	9	10	11	12
Stimulus Length (mm)	2.5	4.5	6.4	8.0	13.1	18.3	23.4	32.6	41.9	52.4	62.7	75.0
Response Duration (msec)	349	422	475	512	601	671	728	812	882	950	1008	1069

After each practice stimulus-response pair, subjects received feedback regarding the correct response duration for the stimulus length. This was done by presenting two brief beeps, whose onsets were temporally separated by an amount of time that matched the stimulus length, as specified by the stimulus-response relation to be learned. After the beeps, subjects received feedback regarding whether the response duration was longer or shorter than the correct target duration. In addition, a score for the response was shown, indicating how close subject's response duration had come to the correct duration. No feedback was given for transfer stimulus-response pairs.

Rationale

As summarized by the literature on category learning and concept formation, cognitive theories of induction have been proposed in terms of two alternative accounts: *exemplar models* and *abstraction models* (Smith & Medin, 1981). Exemplar models assume that natural and artificial categories (e.g., ANIMALS, VEHICLES, FURNITURE, etc.) are learned by storing specific instances of the categories, and that the production of a categorical response to a new stimulus is based on the similarity between the new stimulus and previously experienced instances. In contrast, abstraction models assume that learning a category entails abstracting a prototype or central tendency of the category, and responses to new stimuli are produced on the basis of distances between these stimuli and the prototype.

Here we are concerned about extending these alternative types of models to characterize the learning of continuous stimulus-response relations. For example, in responding to a transfer stimulus, one possibility is that subjects might produce the response duration associated with whichever practice stimulus best matches the transfer stimulus. This would involve an exemplar-based process, and it could lead to increasingly good performance as the subjects get more and more experience at making responses to the practice stimuli. However, the accuracy of responses to the transfer stimuli would still be less than the accuracy of responses to the practice stimuli, even after many learning trials, because the responses to the practice stimuli are not most appropriate for the transfer stimuli.

Another possibility is that subjects may instead use an abstraction-based process instead; they may actually induce the underlying mathematical function that relates the selected stimulus-response pairs. If so, we would expect equally good performance for the transfer and practice stimuli, because the induced function should work just as well regardless of stimulus type. By examining subjects' performance for each stimulus type, we may therefore distinguish between different models of the learning process.

Results and Discussion

Figure 1 presents log response durations averaged across subjects as a function of log stimulus length for Sessions 1 and 5, respectively. The error bars indicate ±1 standard deviation of individual responses pooled across subjects. The dashed lines represent the power function to be learned. We have plotted it here in terms of log-log coordinates because this makes the chosen function appear as a straight line.

Subjects' responses were close to the required responses even in the first session, indicating that the power function was learned quite rapidly. Furthermore, performance for transfer stimulus-response pairs (closed circles) was as good as that for practice pairs (open circles). The difference between mean biases for the practice and transfer pairs was not significant [$F(1,55) = 1.30$; $p > .05$]. Nor was the difference between standard deviations of responses for the practice and transfer pairs significant [$F(1,55) = .05$].

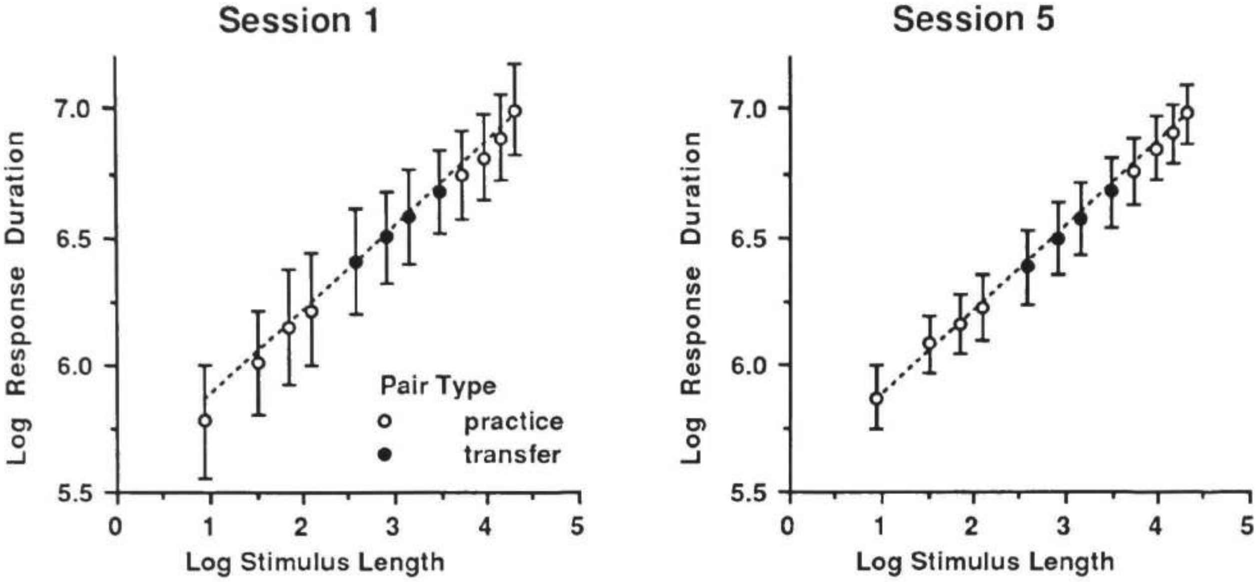

Figure 1. Mean response duration (in $\log_e$ msec) averaged across subjects as a function of stimulus length (in $\log_e$ mm) for the first and last sessions in Experiment 1. The dashed line represents the power function to be learned. The error bars indicate ±1 standard deviation of individual responses pooled across subjects.

Given these results, we have doubts about whether a simple exemplar-based process is the primary mechanism that people use to induce continuous stimulus-response relations. Instead, it seems more likely that such relations are induced through an abstraction-based process as described more fully later (see General Discussion).

EXPERIMENT 2

In subsequent experiments, we have examined whether subjects can accurately induce continuous relations other than the power function used in Experiment 1. Our objective here was to determine how general the abstraction process is. Depending on the nature of the abstraction process, subjects may or may not be able to learn a variety of possible functions.

Method

The basic design and procedure of Experiment 2 were the same as before. However, the underlying relation between the stimulus and response dimensions involved a logarithmic rather than power function. The chosen function was $D = 75 + 223.5 \log_e L$, where D and L denote response duration (in msec) and stimulus length (in mm), respectively. The stimuli were the same as those used in Experiment 1; the range of responses was approximately equal to that of Experiment 1.

Results and Discussion

Log response durations averaged across subjects are plotted in Figure 2 against log stimulus length for Sessions 1 and 5. The dashed curve represents the logarithmic relation to be learned.

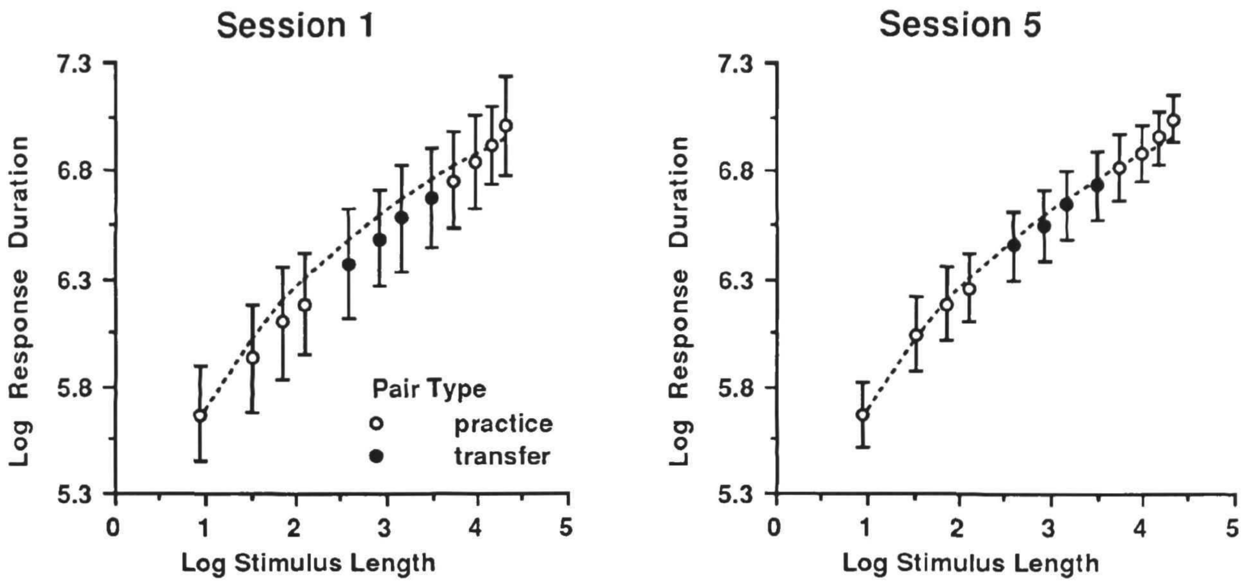

Figure 2. Mean response duration (in $\log_e$ msec) averaged across subjects as a function of stimulus length (in $\log_e$ mm) for the first and last sessions in Experiment 2. The dashed curve represents the logarithmic relation to be learned.

As in Experiment 1, performance for transfer stimulus-response pairs was about as good as that for practice pairs, both in terms of mean bias [$F(1,55) = 3.15$; $p > .05$] and variability [$F(1,55) < 1$]. This provides further evidence of an abstraction-based process. However, unlike in Experiment 1, substantial response biases occurred in Session 1; the observed response durations for the middle stimuli were shorter than required, whereas the observed responses for the short and long stimuli were longer than required. This pattern might result if subjects attempted to fit a power function (which appears linear in log-log coordinates) to the experienced stimulus-response pairs. The magnitude of these biases decreased over sessions [$F(4,20) = 3.03$; $p < .05$], although there still were some residual biases in Session 5.

Overall, it appears that the subjects had an initial bias toward inducing a power stimulus-response relation, but gradually overcame the bias and learned the required logarithmic relation to a relatively close approximation.

EXPERIMENT 3

Experiment 3 was performed to replicate and extend the results of our previous experiments. Here the required stimulus-response relation involved a linear function with a positive intercept. When plotted in log-log coordinates, this function appears curved upward in a mirror image of the logarithmic function used in Experiment 2, which is curved downward. If people indeed have a bias toward inducing power functions, we should observe a systematic pattern of initial bias similar to that found in Experiment 2. Moreover, if people can overcome the bias to learn functional relations other than power ones, then with sufficient practice, they should produce responses according to the present linear function.

Method

The design and procedure of Experiment 3 were identical to those of Experiments 1 and 2, except that the stimuli and responses were related by a linear function with a positive intercept. The stimulus-response relation to be learned here was D = 453.5 + 10.9 L, where D and L denote response duration and stimulus length, respectively. The stimuli were the same as those used before; the responses were approximately equal in range to the previous ones.

Results and Discussion

Figure 3 presents log stimulus length versus log response duration averaged across subjects for Sessions 1 and 5. The dashed curve represents the required linear relation. The results were similar to those of Experiment 2 in all major respects.

Most important, a systematic pattern of response biases, constituting a mirror image of the one obtained in Experiment 2, occurred during Session 1. This pattern supports the hypothesis that people are predisposed toward inducing power functions to relate stimuli and responses. As in Experiment 2, the magnitude of the biases decreased over sessions [$F(4,20) = 11.88$; $p < .0001$]; by Session 5, subjects' responses came close to the required responses. Apparently, the abstraction process used by our subjects is flexible enough to learn various types of relations, even though it is initially biased toward power functions.

GENERAL DISCUSSION

In summary, we have obtained several pieces of evidence suggesting a relatively sophisticated abstraction process for inducing continuous stimulus-response relations. Performance on transfer pairs was as good as performance on practice pairs in all three experiments. Also, subjects' responses revealed certain systematic biases and changes over time that suggest further details about how the abstraction process works.

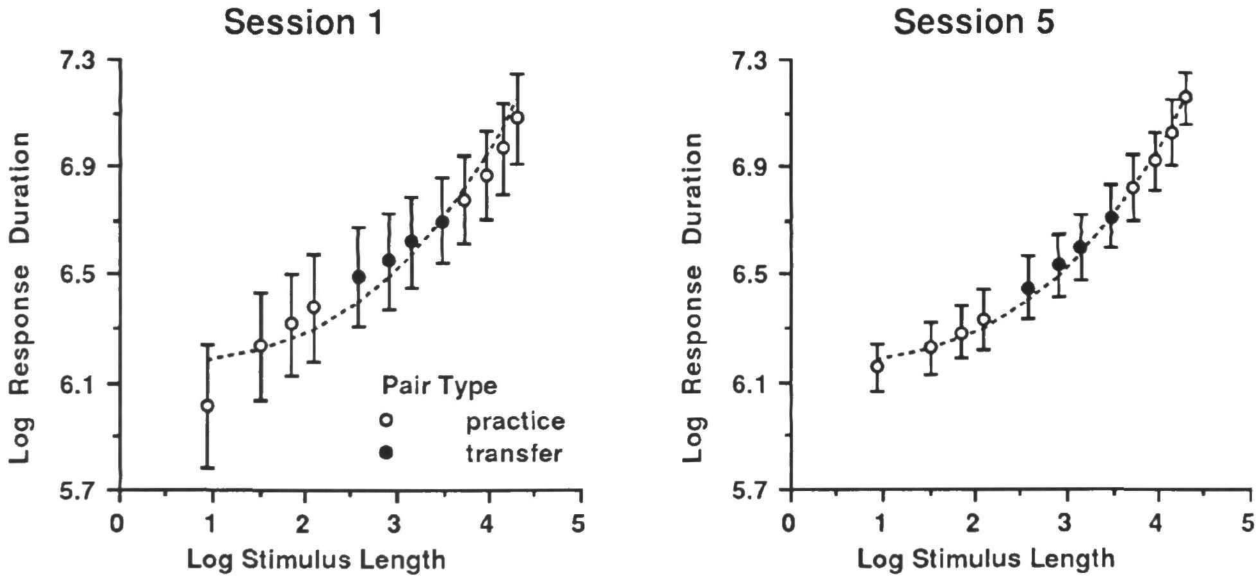

Figure 3. Mean response duration (in $\log_e$ msec) averaged across subjects as a function of stimulus length (in $\log_e$ mm) for the first and last sessions in Experiment 3. The dashed curve represents the linear function to be learned.

A Proposed Model : Adaptive-Regression

To explain our results, we have developed a model of induction called the "adaptive-regression" model that accounts for all major aspects of the obtained data (Koh & Meyer, 1989; Koh, 1989). According to the model, people try to fit a polynomial (e.g., cubic) function to the experienced stimulus-response pairs. The pairs are first transformed logarithmically before being submitted to the fitting algorithm. The algorithm estimates polynomial coefficients so that a weighted combination of 1) the curvature of the fitted function and 2) the summed squared deviations of the fitted function from the experienced stimulus-response pairs is minimized.

Initially, the curvature component of the model has relatively more weight than the squared-deviation component, resulting in a bias toward inducing power functions. This is due to the fact that lines have minimum (i.e., zero) curvature, and that power functions correspond to linear functions in log-log coordinates. As more and more stimulus-response pairs are experienced, however, the squared-deviation component receives relatively more weight, allowing the fitted function to gradually approach the required function.

We have implemented the adaptive-regression model and other models based on exemplar as well as abstraction processes in a computer program; the results clearly favor the adaptive-regression model. The success of this model is illustrated in Figure 4, which presents results from a computer simulation of Experiment 3. The simulated data closely resemble the actually observed data (Figure 3).

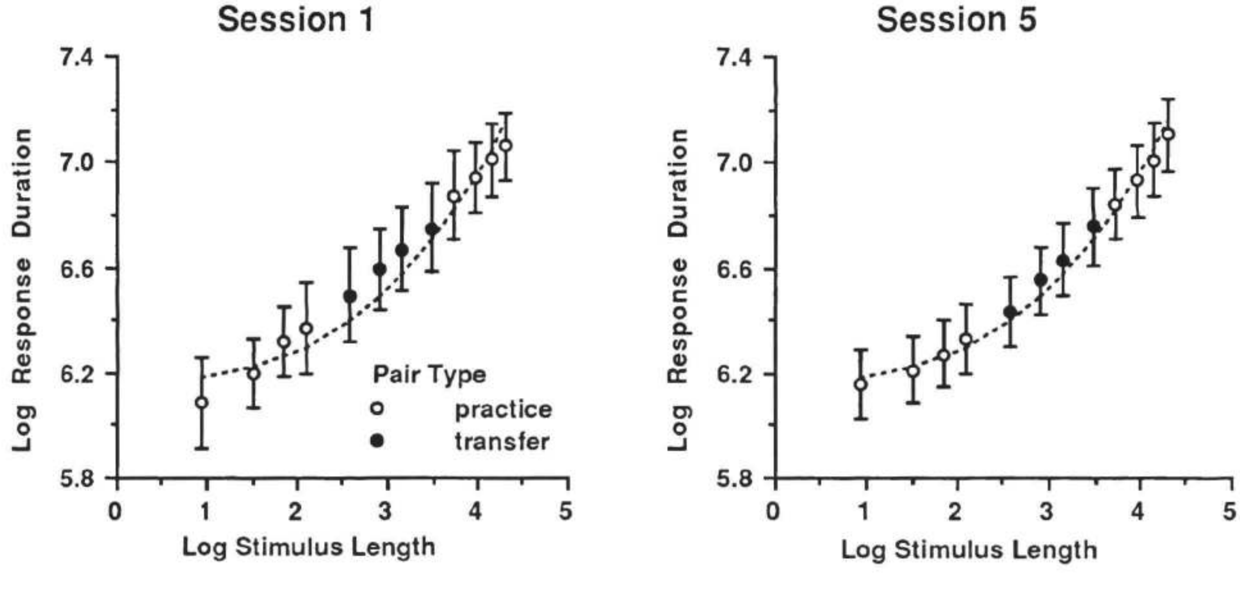

Figure 4. Predictions by the adaptive-regression model for a linear stimulus-response relation used in Experiment 3. Response durations (in $\log_e$ msec) are plotted against stimulus lengths (in $\log_e$ mm).

Relation to Previous Research

The present perceptual-motor learning task is closely related to cross-modality matching tasks for deriving psychophysical functions. Stevens and his colleagues have conducted a series of experiments concerning several sensory modalities, showing that for all of them, matching functions between pairs of modalities come from a family of power functions (Stevens, 1965; Stevens & Marks, 1965). Our results mesh well with Stevens' findings, and together they suggest that people have a natural tendency to establish power relations between pairs of continuous dimensions, and that people learn "natural" relations more readily than others (cf. Shepard, 1981).

Our work is also related to past research on category learning. In recent years, models of category learning based on similarity among perceived and remembered exemplars have received much attention and some empirical support (Estes, 1986; Medin & Shaffer, 1978; Nosofsky, 1984). However, the present results for a perceptual-motor learning task cannot be explained easily by exemplar models. Instead, the results fit quite nicely with the adaptive-regression model, which involves an extensive abstraction process. It would be unappealing to postulate entirely separate inductive mechanisms for category learning and perceptual-motor learning. Developing a unified theory of induction that encompasses both types of learning is therefore an important topic for future research.

AUTHOR NOTE

Support was provided by Grant R01 MH37145 from the National Institute of Mental Health. Kyunghee Koh is now at the Center for Visual Science, University of Rochester. Correspondence should be sent to: David E. Meyer, Department of Psychology, University of Michigan, 330 Packard Road, Ann Arbor, MI 48104.

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