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Effects of preliminary information in a Go versus No-go task *

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A series of studies using a Go versus No-go task examined the question of whether preliminary information available early in the recognition of a stimulus is made available to later processes before stimulus recognition is finished, a question relevant to the controversy between discrete and continuous models. Experiment 1 showed that a Go response is faster following a cue indicating that the response probably would be required than following a cue indicating it probably would not be required. Experiments 2–7 were conducted to find out whether analogous preparation occurred when probability of the Go response was signalled by easily discriminable features of a single stimulus rather than a separate cue. The effect was observed when the easily discriminable features uniquely determined the name of the stimulus letter, but not when they merely indicated that the stimulus name was one of two visually similar letters. These results are consistent with the Asynchronous Discrete Coding model, in which the perceptual system makes available to later processes only preliminary information corresponding to discretely activated stimulus attributes.

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Overview

A question that has attracted considerable interest in recent years is whether preliminary information from a partially recognized stimulus is made available to later processes before perceptual analysis of that stimulus is complete (e.g., Eriksen and Schultz 1979; Meyer et al. 1988b; Miller 1982a, 1988). A number of experimental paradigms have been developed to answer this question; all have focused on the issue of whether preliminary perceptual information can be used to begin the preparation of responses. Various studies have attempted to infer response preparation from observations about the organization of the response system and/or response cuing effects (e.g., Miller 1982a, 1983), from response-competition or dual-task measures of response activation (e.g., Miller 1982c, 1985, 1987a), or from decomposition of speed–accuracy tradeoff functions (e.g., Meyer et al. 1988a; 1984). Still others have attempted to observe response preparation directly using psychophysiological measures (e.g., Coles and Gratton 1986; Coles et al. 1985; Miller and Hackley 1990; Osman et al. 1988).

This article reports findings obtained with a new paradigm for examining effects of preliminary perceptual information on later processing, and these findings extend previously demonstrated effects in three major ways. First, the results demonstrate an effect of preliminary perceptual information in a Go versus No-go task. This effect is perhaps surprising because of the extremely simple response requirements of this task. Also, because of this simplicity, the effect of preliminary perceptual information in this task is difficult to attribute to certain artifactual explanations of some previous response preparation effects (e.g., Reeve and Proctor 1984). Second, the results indicate that the perceptual system sometimes transmits preliminary information about an irrelevant attribute of the stimulus before it has finished processing the relevant attribute(s). In previous studies, preliminary information has always concerned a stimulus attribute that was assigned to some response or response attribute (e.g., hand) by the experimenter's instructions. For example, if subjects responded to stimulus name, then preliminary information about name might cause early response activation (e.g., Coles and Gratton 1986). In the present experiments, however, preliminary information concerned an attribute that was only incidentally correlated with the correct response, not one of the defining criteria for it. Third, certain aspects of the results suggest that in this paradigm preliminary perceptual information affects decision-level processes rather than response preparation processes. Thus, this paradigm may provide a way of observing the transmission of partial information from perceptual processes to decision processes – a type of transmission which has not previously been observed, but only inferred from evidence that preliminary information influences response processes.

By way of introduction, we first outline the controversy between discrete and continuous models and show the relevance of determining whether preliminary perceptual information is made available to later processes. Then, we describe a method of testing for effects of preliminary perceptual information in a Go versus No-go task and report a series of experiments employing this method.

Discrete and continuous models

The distinctions between discrete and continuous models of human information processing (e.g., Eriksen and Schultz 1979; Miller 1982a, 1988; Norman and Bobrow 1975; Sanders 1980; Turvey 1973) have often been drawn very generally, corresponding roughly to the distinction between traditional stage models of reaction time (RT; e.g., Sternberg 1969a, 1969b) and the more recent neurally-inspired, parallel-contingent models (e.g., Eriksen and Schultz 1979; McClelland 1979; Rumelhart and McClelland 1982). Miller (1988, 1990) identified four specific senses in which information processing models can be said to be discrete or continuous, and argued that these senses must be distinguished because a given model can be discrete in some senses and continuous in others.

One of the most important senses in which a model can be discrete or continuous concerns the overall architecture of the processing system within which mental processes are embedded. In sequential architectures, a later process cannot begin until after the termination of all earlier processes on which it is contingent (i.e., from which it receives input; Schweickert 1978; Sternberg 1969a). Each process must finish before the next process can begin, because a process only transmits output when it has finished, or, equivalently, because the later process does not begin until it has received complete information from the earlier one. This architecture can be described as having 'discrete information transmission' between processes (Miller 1988).

In other, more complex architectures, contingent processes may operate with some temporal overlap. To enable temporal overlap of two contingent processes, the earlier one must transmit preliminary partial information to the later one. Given access to partial information, the later one can begin before the earlier one has finished. The most extreme temporal overlap between contingent processes occurs in models with continuous information transmission. In these models each process immediately transmits any partial information that it acquires, so the subsequent process can continuously monitor and use this information (e.g. Eriksen and Schultz 1979; McClelland 1979).

Miller (1982a, 1988) discusses architectures that can be described as intermediate between the extremes of discrete and continuous information transmission. In these types of models a process 'saves up' partial information until it has a certain amount, called an information 'grain', at which point it transmits this information to the next process. As long as the grain size is small enough to allow transmission before the process has completely finished with the stimulus, transmission cannot be said to be fully discrete. To the extent that some information must be saved to make a grain, though, transmission cannot be said to be fully continuous either. On the basis of experimental results Miller (1982a, 1983) argued for a particular intermediate case known as the 'Asynchronous Discrete Coding' (ADC) model. In this model information transmission occurs by means of discrete mental codes for stimulus attributes such as letter name, color, or size. Thus, transmission of information about single-attribute stimuli is discrete, but transmission of information about multi-attribute stimuli takes place attribute by attribute.

The distinction between discrete and continuous transmission is important methodologically as well as theoretically, because the interpretation of RT depends critically on whether the different processes operate sequentially or with some temporal overlap (cf., McClelland 1979; Sanders 1980; Schweickert 1980; Taylor 1976; Wickelgren 1977). In discrete architectures, RT is simply the sum of the times for the various processes required for the task, and there are sophisticated methods for making inferences about individual processes within the architecture (e.g., Estes 1972; Neisser 1967; Shepard and Metzler 1971; Sternberg 1969a, 1969b). In continuous architectures, however, RT is not a simple function of the durations of the mental processes involved in the task, and comparatively complicated methods are needed to study the timecourse of information processing (McClelland 1979; Wickelgren 1977). [1]

It is impossible for any single experimental paradigm to settle the issue of whether transmission is discrete, continuous, or somewhere in between (for a review of alternative paradigms, see Miller 1988). [2] One reason is that different architectures could be used in different tasks, so results from any single paradigm must be generalized cautiously. Another reason is that most, if not all tasks, involve more than two mental processes, and transmission between one pair of processes may be discrete even if transmission between another pair is continuous (Miller 1988). Given the fundamental nature of this issue and the possible complexity of its resolution, it is necessary to develop a variety of different experimental approaches to it.

Effects of preliminary perceptual information

Like a number of previous paradigms for studying discrete versus continuous transmission (e.g., Miller 1982a, 1983, 1987a), the present paradigm was developed to study the transmission of information by the perceptual process. Specifically, we wanted to find out whether, in a simple Go versus No-go task, the perceptual system transmits preliminary information about a given stimulus before perceptual analysis of that stimulus is finished. If it does not, models with discrete transmission are favored; if it does, then models of a more continuous character are required.

[1] As Sanders (1990) has emphasized, however, there are cases in which the Additive Factor Method (Sternberg 1969) may be used even though the architecture is continuous. For example, in the Cascade model of McClelland (1979), the Additive Factor Method can be used when two factors affect processing rates as opposed to asymptotes.

[2] In the remainder of the paper, we will use the phrases 'continuous models' and 'discrete models' as short-hand for models with relatively continuous and discrete transmission, respectively. It should be emphasized that we are only referring to transmission, not the other model characteristics which may be discrete or continuous.

Perceptual information is 'preliminary' if it becomes available before the end of task-relevant perceptual analysis of a stimulus. [3] If a task requires discrimination of shape and color, for example, the preliminary information is that conveyed by whichever attribute the perceptual system identifies first (i.e., the 'faster' one). If the slower attribute is irrelevant, however, then there is no preliminary information, because the perceptual system can stop as soon as the faster one is determined.

Previous studies suggest that some types of preliminary perceptual information affect response preparation in a variety of paradigms (see Miller, 1988, for a review). This evidence contradicts discrete models in which the perceptual system transmits no information until identification of the entire stimulus is complete. If there were no preliminary perceptual output, there could be no response preparation based on that output.

On the other hand, there are several types of preliminary perceptual information that do not seem to produce response preparation in these same paradigms. For example, there is no effect of preliminary perceptual information indicating that the stimulus is one of two visually similar letters or that the stimulus is one of two squares differing slightly in size. These findings support the ADC model, in which the perceptual system only transmits output when it has fully recognized a distinct attribute used in coding the stimulus (Miller 1982a, 1983, 1988). If continuous flow or cascade-type models were correct (Eriksen and Schultz 1979; McClelland 1979), then analogous response preparation effects should be found with any types of preliminary information, not just those corresponding to distinct stimulus attributes.

It is generally assumed that a decision process intervenes between perceptual analysis and response preparation, at least with arbitrary S–R mappings (e.g., Sanders 1980; Smith 1968). Thus, when preliminary perceptual information does cause preparation of arbitrary responses, as in the studies just described, it follows that there must also have been some decision-level processing before perceptual analysis was complete. One of the goals of the present set of experiments was

[3] Note that information provided by a separate cuing stimulus, presented prior to the imperative stimulus, does not count as preliminary perceptual information for the issue of discrete versus continuous transmission (Miller 1982a, 1988). The use of preliminary information provided by a cue does not show that the perceptual system transmits partial information during its analysis of a single stimulus.

to document the effect of preliminary information on decision processes directly rather than through its influence on response processes. This seems especially important because of the existence of cases in which preliminary perceptual information does not cause response preparation. It is possible that in these cases there is an effect of preliminary information at the decision level, but that this effect is blocked before reaching the response level. This possibility can only be tested by looking directly at effects of preliminary perceptual information on decision making. The Go versus No-go task seemed like a good candidate for documenting a decision-level effect, because the post-decisional processing done after stimulus onset is much simpler than that found in tasks with larger response sets (e.g., Rosenbaum 1983).

Another purpose of these experiments was to look for an effect of preliminary information about a task-irrelevant attribute of the stimulus. [4] In previous experiments, preliminary information has been shown to have effects when it conveys a task-relevant attribute of a relevant stimulus (e.g., Miller 1982a, 1983) and when it conveys a task-relevant attribute of an irrelevant stimulus (e.g., Coles et al. 1985; Miller 1987a). In the latter case, though the preliminary information was potentially misleading because it came from an irrelevant stimulus, it was at least concerned with the relevant attribute of this stimulus. Thus, based on previous results, we know that the perceptual system transmits preliminary information about relevant attributes before recognition of the whole stimulus is finished. Results obtained with the present paradigm indicate that it also transmits preliminary information about task-irrelevant attributes.

Effects of preliminary information in a Go versus No-go task

The present experiments measured effects of preliminary perceptual information in a Go versus No-go task (Donders', 1868/1969, type C), for which the single response is made to some stimuli (Go) but not others (No-go). Donders suggested that, at a gross level of analysis, this

[4] Various definitions of task relevance are possible. In this paper, a task-relevant attribute meets two plausible criteria: (1) knowledge of the attribute is necessary for correct responding, and (2) the subject is instructed to use the attribute in selecting the response. Attributes referred to as task-irrelevant satisfy neither of these criteria.

task requires only two stages: perceptual analysis and response execution. The existence of these two stages is supported by strong effects of stimulus and response factors (e.g., Callaway 1984; Van Galen 1990), and the latter stage can also be monitored with a variety of psychophysiological measures (e.g., Brunia 1984; Brunia and Boelhouwer 1988; Van der Molen et al. 1989). As suggested by Donders' early critics (e.g., Wundt 1883, cited by Woodworth 1938), however, the Go versus No-go task apparently requires a third stage in addition: a response selection or decision stage intervening between perception and response execution. The existence of this stage is suggested by evidence that the No-go response is an active process (e.g., De Jong et al. 1989; Logan et al. 1984; Richer et al. 1983), which implies that subjects must make an explicit decision between the two response alternatives. In fact, it appears that the decision between performing and withholding a response is very similar to that between two overt responses (Hackley et al. 1990). The presence of a decision stage in the Go versus No-go task is also suggested by the finding of refractory effects following No-go stimuli (e.g., Bertelson and Tisseyre 1969; Fraisse 1957; Smith 1967), especially in combination with evidence that perceptual analysis is prior to the bottleneck that produces refractory effects (e.g., Pashler 1984, 1989; Pashler and Johnston 1988). Finally, the operation of a decision process in this task is suggested by effects of decision variables like memory set size, even though these effects are not necessarily the same as those found in other tasks (Egeth et al. 1972; see also Van der Heijden and La Heij 1983).

Because only one overt response is possible in this task, post-perceptual processing is clearly very simple. In principle, however, preliminary perceptual information could still influence post-perceptual processes before perceptual analysis was complete. This influence would have observable effects on RT if it involved an adjustment of overall preparation for the Go response. In fact, there is considerable evidence that central and/or motor preparation do vary substantially even during simple RT tasks (e.g., Näätänen and Merisalo 1977). For example, the classic finding that simple RT increases with the duration and variability of the foreperiod (e.g., Klemmer 1957) suggests that subjects enter a state of optimal preparation at the moment when they most expect the imperative stimulus (Welford 1976), possibly because it is difficult to maintain a high degree of preparation indefinitely (Näätänen 1971). Sanders (1965) also showed that simple RT is sensitive to activities that subjects are asked to perform just before the trial starts, indicating that subjects carry out some preparation even before the warning signal. Recently, Phillips and Glencross (1985) showed that movements cannot be entirely preprogrammed in either Go versus No-go or simple RT tasks, suggesting that post-perceptual processes must carry out some movement programming after stimulus onset.

In the present experiments, we attempted to induce post-perceptual preparation by manipulating the conditional probabilities of Go and No-go responses given preliminary information. On some trials the preliminary information indicated that the probability of a Go response was 0.9 and the probability of a No-go response was 0.1, and on these trials it was expected that subjects would be relatively highly prepared to make the Go response. On other trials preliminary information signalled that the probability of a No-go response was 0.9 and the probability of a Go response was 0.1, and on these trials subjects should be relatively poorly prepared for the Go response. Because of differential preparation, Go responses should be faster when the probability of a Go response (Go probability) is high than when it is low. Thus, the effect of Go probability on mean RT is the preparation effect of primary interest in these experiments.

On an individual trial, Go probability was signalled in different ways across experiments. In the first experiment, Go probability was indicated by a separate cue presented before the imperative stimulus. [5] This cuing experiment simply showed that Go probability had the expected effect on preparatory state and that this effect showed up in RT.

The discreteness or continuity of transmission was examined in experiments 2–7. In these experiments, the cues and imperative stimuli were presented simultaneously within a single physical stimulus. In experiment 2, for example, the stimuli were colored letters. The easily discriminable dimension of letter name served as the cue, and the value of this dimension indicated the Go probability for the current trial. The more difficult color discrimination provided imperative information,

[5] In this article, the 'imperative stimulus' or 'imperative attribute' is the stimulus or attribute which determines whether the subject is supposed to make the Go or the No-go response. Some previous authors have reserved the term 'imperative' for stimuli demanding the Go response, contrary to the present usage.

because subjects were instructed to make the Go response to letters of one color but not the other.

With such stimuli, it was assumed that the perceptual system would finish recognizing the easy dimension earlier and the difficult dimension later. The question, then, was whether the early information provided by the easily discriminable cuing attribute would have an influence on post-perceptual processes even before the imperative attribute had been recognized.

According to models with fully discrete transmission, the Go probability effect should not occur when the cuing and imperative information are bound together in a single stimulus. In these models, later processes do not begin until perceptual processes have finished with recognition of the whole stimulus. By that time, of course, the imperative attribute is known, so there is no need for preparatory adjustments based on probabilistic cuing information.

Preliminary perceptual information could produce a Go probability effect according to models with continuous transmission and, with certain types of preliminary information, according to the ADC model (Miller 1982a, 1983). According to these models, preliminary information would be available to later processes for preparatory adjustments even before perception of the stimulus finished, so it should act just like a cue. If preparatory adjustments do occur, then responses should be faster when the probability of a Go response is high (as signalled by the cuing attribute) than when it is low.

Other effects confounded with Go probability

The manipulation of the conditional probability of a Go response necessarily requires variation in absolute stimulus probability, and this variation raises three related problems. First, stimuli indicating high and low Go probabilities tend to have high and low absolute probabilities (but see experiment 3 for a counterexample), and stimulus probability is known to affect RT (e.g., Miller and Pachella 1973). Because we wish to attribute the effect of Go probability to post-perceptual preparation resulting from preliminary output, we must show that the effect cannot simply be explained in terms of stimulus probability. Fortunately, it is possible to construct a condition that controls for the confounded effect of stimulus probability, and this condition is included in each experiment.

Second, differential stimulus probability provides differential practice in making the various task-relevant discriminations. In the present usage, the distinction between a probability effect and a practice effect is that the former is specific to the particular stimulus item, whereas the latter may depend on the probabilities of other stimuli that are difficult to discriminate from the one being tested. For example, Miller (1979) found that in some cases the RT to one stimulus was influenced by the probability of a visually similar stimulus, and the design of the present experiments provides an opportunity for similar effects to occur. We will defer detailed discussion of these effects until experiment 4, where we have reason to believe that they are present.

Third, differential stimulus probability necessarily leads to differential proportions of repetitions across conditions (Kornblum 1973). To some extent, the presence of sequential effects is secondary to our main concerns, because effects of preliminary perceptual information are important whether they are produced directly by probability or indirectly through changes in the proportions of repetitions. Nonetheless, the extent to which the various types of probability effects are due to repetitions will be examined. This analysis is presented in a separate section, after the average results have been described for all experiments.

Experiment 1. Cued Go probability

The primary purpose of this experiment was to verify that, in a Go versus No-go task, responses are faster when the probability of a Go response is higher. Most previous evidence of response probability effects has been obtained with between-block or between-subject variations in probability (e.g., Van der Molen et al. 1989). The logic of the present paradigm, however, requires that probability have an effect when it is cued on a trial-by-trial basis, because we wish to study rapid adjustments made in response to changing Go probability. A secondary purpose was to determine how the Go probability effect, if present, would depend on the amount of time between cue and imperative stimulus.

The informative cue was a yellow outline rectangle which was either tall or wide. After a stimulus onset asynchrony (SOA) of 50, 100, 250, 400, or 750 ms, this rectangle was filled in to produce a solid blue or green rectangle of the same shape, and subjects were to respond to solid rectangles of one color (Go color) but not the other (No-go color). The shape of the rectangle cue informed the subject of the probability of a Go

Table 1
Stimulus probabilities for a sample subject in experiment 1.

	Imperative attribute	
	Green/Go	Blue/No-go
	Experimental condition	
Cuing attribute		
Tall	0.45	0.05
Wide	0.05	0.45
	Control condition	
Cuing attribute		
Tall	0.45	0.45
Wide	0.05	0.05

response on that trial. For each subject, one shape (high Go probability) indicated that there was a 90% chance that the Go response would be required, and the other shape (low Go probability) indicated that there was a 10% chance that the Go response would be required.

Stimulus probabilities were varied in order to produce a cuing relationship between rectangle shape and probability of a Go response. The probabilities for a sample subject are shown in the top half of table 1 (experimental condition), and for this subject the Go color was green and the No-go color was blue. Furthermore, the tall rectangle cued a high probability of a Go response, because the Go color was presented on 90% of the trials with a tall rectangle as the cue. Conversely, the wide rectangle cued a low probability of a Go response, because it was usually filled with the No-go color.

Method

Apparatus and stimuli

Stimuli were presented and responses and response latencies recorded by an IBM-PC compatible computer equipped with an Enhanced Graphics Adaptor and attached to an NEC Multisync display monitor. The Go response was made by pressing the / (slash) key on the standard computer keyboard with the right index finger.

Both cues and imperative stimuli were rectangles measuring approximately 1.1 by 0.4 degrees of visual angle, oriented so that the long side was vertical (tall rectangles) or horizontal (wide rectangles). Cues were yellow outline rectangles, and imperative stimuli were solid blue or green rectangles.

Subjects and Procedure

Subjects were 24 undergraduates recruited on the campus of the University of California, San Diego. Subjects were randomly divided into four groups on the basis of the assignment of stimulus colors (blue and green) to responses (Go and No-go), and the assignment of rectangle shapes (tall and wide) to Go probability (90% vs. 10%). Each subject served in a single session lasting about 50 min, and received either a monetary payment or credit toward an undergraduate course requirement.

Each session was composed of three blocks of 200 experimental trials. Blocks began with four warmup trials randomly selected with replacement from the experimental trials, and a new random order of trials was generated for every block.

Each block included the 20 types of trials defined by a factorial combination of five SOAs and four combinations of cues and imperative stimuli. Two of the combinations were tested 18 times at each of the five SOAs: the high Go probability rectangle cue with the Go color, and the low Go probability rectangle cue with the No-go color. The other two combinations were tested twice at each SOA: the high Go probability rectangle cue with the No-go color, and the low Go probability rectangle cue with the Go color. The imperative stimulus was always constructed by filling in the rectangle cue, without any change in shape (tall vs. wide).

A trial began with the display, for 800 ms, of a plus sign that served as a fixation point and warning signal. The rectangle cue appeared 500 ms after the offset of the warning signal, and remained on the screen for the appropriate SOA. At the end of the SOA, the outline rectangle cue was filled in with the appropriate color for that trial, and the resulting figure remained on the screen until the subject responded, or for 1.5 s, whichever came first. At stimulus offset, accuracy feedback was displayed for 600 ms following correct responses and 1.8 s following errors. Trials on which the response was made in less than 100 ms or more than 1.5 s were discarded and rerun at a randomly selected later point in the block. The intertrial interval was approximately 500 ms.

Subjects were told that they were to respond as quickly as possible to one color of solid rectangle but not to the other color, and that it was very important to avoid false reactions. The outline rectangle cue was described only as a signal to get ready for a solid rectangle. We did not explicitly inform subjects of the relationship between cue shape and Go probability, because we did not wish to induce any explicit strategy of shape processing. The importance of this factor will be examined in future research. Nonetheless, we expected that subjects would quickly learn the predictive relationship between cue shape and Go probability, consciously or not (cf., Miller 1987b). After this learning occurred, subjects should attain more preparation for the Go response when the probability of that response was high than when it was low. Naturally, increased preparation should speed Go responses.

Results and Discussion

Average RTs of Go responses and percentages of correct responses (PCs) were computed for both Go and No-go trials for each subject, block, SOA and Go probability.

Fig. 1 shows average RT as a function of SOA and Go probability. A repeated measures analysis of variance (ANOVA) showed reliable effects of SOA, $F(4,92) = 48.269$, $\text{MSE} = 1490.8$, $p < 0.001$, Go probability, $F(1,23) = 34.694$, $\text{MSE} = 3178.8$, $p < 0.001$, and their interaction, $F(4,92) = 5.5501$, $\text{MSE} = 1589.9$, $p < 0.001$. Planned comparisons indicated that the effect of Go probability was not significant at the 50 ms SOA, but was significant at the 100 ms SOA, $F(1,23) = 4.7205$, $\text{MSE} = 2229.3$, $p <$

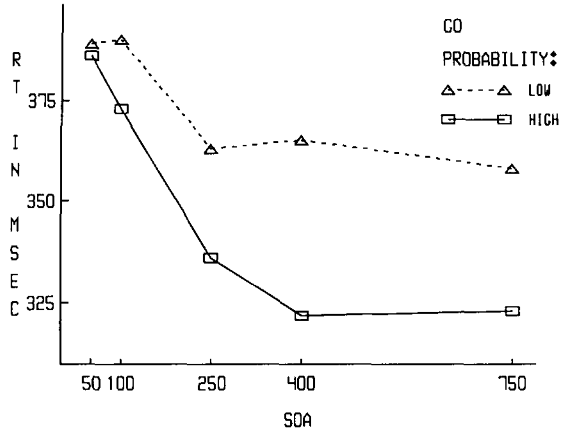

Fig. 1. Experiment 1. Reaction time (RT) as a function of (a) stimulus onset asynchrony (SOA) between cue and imperative stimulus, and (b) probability of a Go response given the cue.

0.040, and highly significant ($p < 0.005$) at SOAs of 250 ms and more. There was also a significant block effect, $F(2,46) = 5.3877$, MSE = 3408.0, $p < 0.01$, with average RTs increasing a total of 17 ms across the three blocks, possibly due to boredom or fatigue, and a significant interaction of block and SOA, $F(8,184) = 1.9974$, MSE = 1552.0, $p < 0.05$. A plot of the latter interaction showed no systematic change in the effect of SOA across blocks, or *vice versa*, and we believe it to be a type I error.

Responses were essentially perfect on Go trials, with less than 0.1% errors of response omission (i.e., failure to respond within the 1.5 s deadline). The rate of errors on No-go trials (errors of commission or false alarms) averaged 2.9%. This error rate was significantly greater when the rectangle cue indicated high rather than low Go probability (5.1% vs. 0.6%), $F(1,20) = 16.3$, MSE = 225, $p < 0.001$. More false alarms were also committed at longer SOAs, $F(4,80) = 2.7$, MSE = 110, $p < 0.05$, especially when Go probability was high, $F(4,80) = 2.27$, MSE = 104, $p < 0.10$. This effect was quite clear in spite of the marginal significance of the interaction. Fewer than 1% false alarms were committed at any SOA when Go probability was low, whereas 1.4%, 4.9%, 5.6%, 4.9%, and 9.0% were committed at the five SOAs when Go probability was high.

The highly reliable effects of Go probability on RT and proportion of false alarms have three clear implications for the present purposes. First, they indicate that subjects learned about the relationship between cue shape and the probability of a Go response, even though this relationship was not described in the instructions. This paradigm thus provides another example of incidental learning of correlations between stimulus features and responses (Miller 1987b).

Second, they indicate that responses and their latencies are influenced by the probability of a Go response in a Go versus No-go task, even when Go probability changes from trial to trial and there is relatively little time for preparation after the new probability is signalled. In particular, it is clear that some type of response readiness was increased when Go probability was high, leading to faster Go responses and more false alarms, relative to the situation with low Go probability. Thus, this task provides another situation in which partial advance information or trial-by-trial cuing of relevant probabilities affects performance (e.g., Hackley et al. 1990; Logan and Zbrodoff 1982; Posner et al. 1978; Sanders 1971).

Third, the increase in Go probability effects with SOA suggests that these effects are produced by very rapid preparatory adjustments. That the effects were obtained at an SOA as short as 100 ms suggests that even brief preparatory adjustments can have sizable effects on RT and false alarms, which bodes well for the sensitivity of the paradigm for detecting effects of preliminary perceptual output.

Part of the effect of SOA may have been due to the use of aging foreperiods (e.g., Luce 1986). In this experiment the conditional probability that the imperative stimulus would appear, given that it had not yet appeared, increased from 0.2 at the SOA of 50 ms to 1.0 at the SOA of 750 ms. To some extent, then, the faster responses observed with longer SOAs may reflect increasing readiness as a function of the greater objective likelihood of imperative stimulus presentation (e.g., Näätänen 1971). It would appear that these effects were quite small, however, possibly due to the short, fixed intertrial intervals. For example, although the conditional probability doubled in size between the 400 and 750ms SOAs, overall RTs changed very little. More importantly, our conclusions about cuing effects are based on the differential effects of high- and low-probability cues at a given SOA, and the effects of aging foreperiods should cancel out with respect to this difference.

It is necessary to consider an artifactual explanation for the Go probability effect that might vitiate our interpretation in terms of preparatory processes. Specifically, the Go probability effect could simply be a result of variation in stimulus probability, rather than in the conditional probability of the response. After all, the stimulus combination of high Go probability shape and Go color occurred nine times as often as that of low Go probability shape and Go color. Perhaps the faster responses to the former combination (i.e., the Go probability effect) reflect faster processing of this frequently seen combination (e.g., faster recognition) rather than preparation based on the high likelihood of a Go response following the cue. Though it would be more difficult, this explanation might also be extended to account for the false alarm differences.

This explanation does not seem likely in view of the dependence of the effects on SOA, which suggests effects arising during the trial (i.e., preparatory processes) rather than before it. Nonetheless, a stimulus probability control condition was run to examine this explanation, using revised stimulus probabilities shown in the lower half of table 1. In this condition the Go stimuli were the same as in the experimental condition, and they occurred with the same probabilities. Thus, if simple stimulus probability were responsible for the effects seen in the experimental condition, then comparable effects should be seen in this control condition. However, the probabilities of the No-go stimuli were reversed, so that shape was no longer informative about Go probability. For example, if a subject saw 45% tall rectangles in the Go color and 5% wide ones, he also saw 45% tall rectangles in the No-go color and 5% wide ones. Because shape no longer cues a response, any effect stemming from the hypothesized response-related preparation should disappear in this control condition.

In fact, there was no effect of stimulus probability in the control condition. Responses averaged 394 ms to high probability rectangles and 395 ms to low probability rectangles, ($F < 1$). There were fewer than 1% errors of omission or false alarms, with no effect of probability on either. Thus, the Go probability effect observed in experiment 1 was truly an effect of conditional response probability, as indicated by the cue, rather than a priori stimulus probability. In addition, the main effect of SOA was comparable to that observed in the experimental condition, but there was no interaction of SOA with probability.

Experiment 2. Letters varying in name (cuing attribute) and color (imperative attribute): Two alternative colors

Experiment 1 showed that RTs are influenced by an advance cue that indicates the probability of a Go response. Experiments 2–7 used this effect to examine the discreteness or continuity of the transmission of information about a single stimulus out of the perceptual process. In general, the question is whether an easily recognized attribute of a single stimulus (i.e., preliminary perceptual information) can have an effect comparable to that of an advance cue. If so, for what kinds of attributes can this occur? The main difference from experiment 1 is that in the subsequent studies the cuing and imperative information were bound together in a single stimulus – generally in separate attributes. An easily discriminable attribute served as the cue, indicating the probability of a Go response, and a difficult-to-discriminate attribute served as the imperative stimulus, indicating with certainty whether or not the Go response was to be made.

In experiment 2 the stimuli were the letters S and T, which could be presented in either of two colors. As in the previous experiment, the subject was to respond to one color but not the other. Across trials one letter usually occurred in the Go color and the other letter usually occurred in the No-go color, so letter name indicated the probability of the Go response. Logically, then, letter name was a cue analogous to rectangle shape in experiment 1, except that this cue was presented together with the imperative attribute (color).

The predictions follow from the results of the cuing experiment. If letter name is used to adjust response readiness before color information is available, then Go probability should have an effect in this experiment just as it did in the cuing experiment. Specifically, Go responses should be faster when letter name indicates that the Go response is probable than when letter name indicates that the Go response is improbable. Just as rectangle shape cued subjects to adjust their preparation for the Go response, so too should letter name perform this cuing function if it is available to post-perceptual processes before the color discrimination has been made. Early information indicating that there is a high probability of a Go response should produce especially fast responses on Go trials and relatively many false alarms on No-go trials. Conversely, early information indicating that there is a low probability of a Go response should produce relatively slow responses on Go trials (and possibly more errors of omission on Go trials).

From the hypothesis that letter name alters response readiness, it is also reasonable to predict that the Go probability effect should increase with the difficulty of the relevant discrimination. Making the relevant discrimination more difficult makes this information become available later, relative to the cuing information, just as the SOA manipulation did in experiment 1. Thus, like increasing SOA, reducing the discriminability of the relevant attribute should cause an increase in the effect of the cuing information.

This prediction was tested by varying the difficulty of the color discrimination. In the condition with an easy color discrimination, the two alternative colors were red and green; in the condition with a difficult color discrimination, they were blue and white. To verify our introspections that these discriminations were both harder than that of S versus T and that blue/white was harder than red/green, a pilot experiment was conducted. In this experiment subjects made two-choice responses based on one stimulus dimension at a time, and the irrelevant dimension varied randomly. Pilot testing showed that the S versus T discrimination required an average of 424 ms, the red versus green discrimination required an average of 449 ms, and the blue versus white discrimination required an average of 551 ms. Based on the pilot experiment, we estimate there should be about 25 ms for Go preparation with the easy color discrimination (449 minus 424) and about 127 ms with the difficult one (551 minus 424).

If, on the other hand, letter name is not used to adjust response readiness before color information is available, there is no reason to expect either a Go probability effect or an interaction of Go probability with color discriminability. Even though cuing information does have an effect when presented in advance of the stimulus (experiment 1), it is not clear why it should have such an effect when imperative information becomes available to the decision level at the same time as the cuing information. Under these circumstances, there is no reason for any but the relevant imperative information to be processed.

Method

A new group of 32 subjects was tested using the same apparatus and general procedure used in the previous experiment. For half of the 32 subjects, the first two blocks required the easy color discrimination and the last two blocks required the difficult color discrimination, whereas for the other half this order was reversed. Also counterbalanced across subjects were (1) whether S or T cued a high Go probability, (2) whether red or green commanded the Go response in the easy discrimination condition, and (3) whether blue or white commanded the Go response in the difficult discrimination condition. The letters were approximately 1.7 deg high and 0.75 deg wide.

Each subject was tested in four blocks of 160 trials. Within each block there were 72 presentations of each of the two frequent stimulus combinations: the letter cuing high Go probability in the color commanding the Go response, and the letter cuing low Go probability in the color commanding the No-go response. There were eight presentations of each of the two infrequent stimulus combinations: the letter cuing high Go

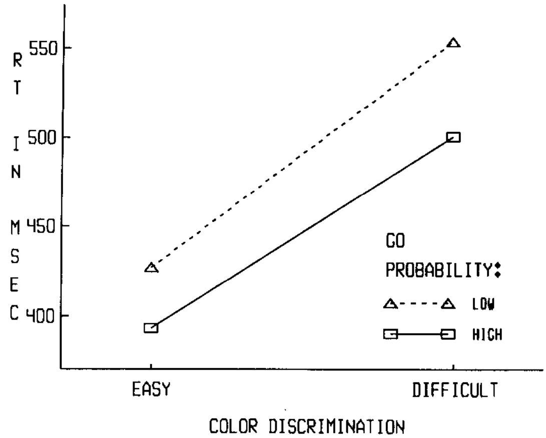

Fig. 2. Experiment 2. Reaction time (RT) as a function of (a) difficulty of the color discrimination, and (b) probability of a Go response given the letter name.

probability in the color commanding the No-go response, and the letter cuing low Go probability in the color commanding the Go response.

Results and Discussion

Fig. 2 shows average RT as a function of color discriminability and Go probability. A repeated-measures ANOVA was computed, including the between-subjects factor of order (easy discrimination first or second). This analysis indicated that Go responses were significantly faster when letter name indicated high Go probability (446 ms) than when letter name indicated low Go probability (490 ms), $F(1,30) = 50.904$, MSE = 1199.8, $p < 0.001$. The 116 ms effect of color discriminability was also highly significant, $F(1,30) = 68.814$, MSE = 6304.6, $p < 0.001$. As shown in fig. 2, the effect of Go probability was larger when the color discrimination was difficult (53 ms) than when it was easy (34 ms), $F(1,30) = 4.4799$, MSE = 700.97, $p < 0.05$.

Errors of omission were rare. There were about 1.5% of such errors when Go probability was low versus 0.4% when it was high, $F(1,30) = 4.5188$, MSE = 8.23, $p < 0.05$. An effect of about the same size was found for discriminability, but it was not statistically reliable, ($p > 0.10$), possibly due to a ceiling effect.

Errors on No-go trials (i.e., false alarms) were more common, averaging about 4.3% overall. In the first block of the low discriminability condition, there were 16% false alarms to the letter name with high Go probability, but there were less than 7% false alarms in all of the other combinations of practice, discriminability, and Go probability. This result caused statistical significance ($p < 0.05$) for all of the main effects and two-way interactions involving these factors, as well as the three-way interaction.

As in the cuing experiment, the effect of Go probability on both RT and false alarms suggests that cuing information was used to adjust response readiness. This conclusion is much more interesting in experiment 2, however, because it means that cuing information has an effect even when it is bound together with imperative information, the former contained in an easily discriminable attribute and the latter contained in a difficult-to-discriminate attribute. This, in turn, suggests that post-perceptual processes receive perceptual information about an easily discriminable attribute even while the perceptual system continues analyzing a difficult-to-discriminate attribute. The increase in Go probability effect with difficult color discriminations is consistent with this hypothesis, because a more difficult color discrimination would allow more time for preparatory adjustment. Other explanations of this interaction are also possible, however, because preparatory adjustment may directly influence a mechanism that is also sensitive to color discriminability.

As in the previous experiment, it is necessary to consider the possibility that the Go probability effect is simply one of stimulus probability rather than evidence that cuing information provided by letter name was used to adjust the response readiness. After all, Go stimuli with the letter name indicating high Go probability occurred nine times as often as Go stimuli with the letter name indicating low Go probability. Perhaps the faster responses to the former stimuli than the latter were only a reflection of their higher probability of occurrence.

A control condition was run to test this explanation. In this experiment a high probability letter was presented on 90% of the trials and a low probability letter was presented on 10% of the trials. Each letter was equally likely to be presented in the Go color and the No-go color, so letter name did not cue the probability of the Go response.

The results of the control condition, shown in fig. 3, are qualitatively similar to those of the experimental condition, suggesting that stimulus probability may indeed have been responsible for at least some of the effects. Responses were 18 ms faster to the high probability letter than to the low probability letter, $F(1,30) = 10.464$, MSE =

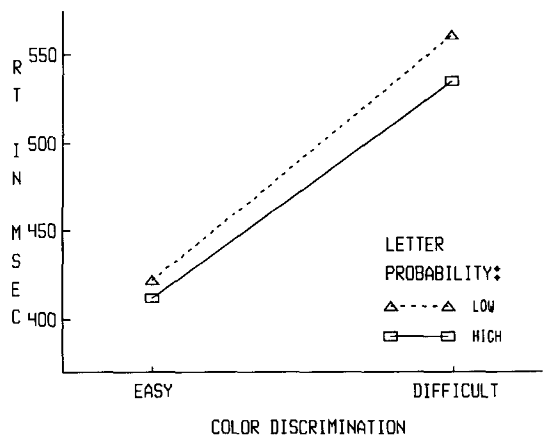

Fig. 3. Experiment 2 (probability control condition). Reaction time (RT) as a function of (a) difficulty of the color discrimination, and (b) probability of a particular letter name.

1060.8, $p < 0.005$, and 130 ms faster with the easy color discrimination than with the hard one, $F(1,30) = 90.044$, MSE = 6003.1, $p < 0.001$. Furthermore, the probability effect was larger with the difficult color discrimination (26 ms) than with the easy one (10 ms), $F(1,30) = 4.5696$, MSE = 434.28, $p < 0.05$.

Although stimulus probability had an effect on RT in the control condition, this effect was too small to explain the much larger effect of Go probability found in the experimental condition. The difference in RT between the high and low probability Go trials was almost 2.5 times as large in the experimental as in the control condition, $F(1,60) = 8.8913$, MSE = 1130.3, $p < 0.005$. On the other hand, the overall RTs and the effects of color discriminability were quite comparable in the two conditions, so there is no reason to expect smaller effects per se in the control condition. Thus, it seems reasonable to conclude that letter name did have a response cuing effect that combined with the effect of simple probability. The error data support this conclusion, since probability did not influence the percentage of false alarms in the control condition as it did in the experimental condition.

It is interesting that an effect of letter probability on RT was found in the stimulus probability control condition for experiment 2 but not for experiment 1. In both experiments subjects decided whether to respond on the basis of stimulus color, whereas stimulus form (i.e., rectangle shape or letter identity) was irrelevant to the task. Yet in the former experiment responses were equally fast to high and low probability forms, whereas in the latter experiment responses were faster to high than low probability forms.

One plausible explanation for this difference is that color judgments were dependent on form in experiment 2 but not in experiment 1, because of the exact forms used. In experiment 1 the forms were solid color patches varying in overall orientation, but subjects could get form-independent color samples by attending to a circular region immediately around the fixation point. Furthermore, these color samples would tend to appear highly saturated because they occupied solid regions of space. With these stimuli, subjects could get essentially the same color samples regardless of stimulus form, so it is not surprising that form probability had no effect. In experiment 2, on the other hand, the forms were line drawings of letters, occupying slightly different regions of visual space, and lines were a single pixel wide (less than 0.05 degree of visual angle). To take in an adequate color sample for discrimination, subjects might well have to attend to and somehow aggregate over the specific form presented. In this case, form probability might have an effect because subjects were perceptually more prepared for the high probability form.

Experiment 3. Letters varying in name (cuing) and color (imperative): Four alternative colors

The results of experiment 2 and its stimulus probability control appear to contradict fully discrete models by suggesting that preliminary information about letter name is used to adjust response readiness before the color discrimination is finished. We must consider two possible explanations of the results in terms of a fully discrete model, however. The first attributes the effect entirely to a decision stage which does not begin until perceptual analysis of the whole stimulus is complete, and the second attributes the effect to a criterion adjustment within the perceptual process itself.

The first discrete explanation is that letter name has a Stroop-like effect at the decision level after perceptual analysis is complete. On this view, both attributes are made available to the decision process at the same time, but the Go decision is reached more quickly when the Go color is accompanied by a letter name correlated with the Go rather than the No-go response. In support of this model, one might cite the common findings of effects of irrelevant information on choice RT (e.g., Eriksen and Eriksen 1974; Stroop 1935).

There are two arguments against the Stroop explanation of the Go probability effect observed in experiment 2. The first is that irrelevant information should have little influence on the decision in a Go versus No-go task. With such a simple decision to be made, it is hard to see how the sizeable effects of Go probability observed here could arise after the imperative attribute had been recognized. This claim receives support from evidence in other paradigms that Stroop-like effects of irrelevant information decrease as the decision requirements of the task are simplified. For example, in a Go versus No-go version of the Eriksen and Eriksen (1974) selective attention task, Grice et al. (1982a) found no response-compatibility effect of the irrelevant flanker letters. Similarly, irrelevant stimulus location information produces less interference in a Go versus No-go reaction task than in a choice reaction task, and virtually no interference in a simple reaction task (Callan et al. 1974). Finally, no effect of Go probability was obtained at the 50 msec SOA in experiment 1.

The second argument against the Stroop interpretation of the Go probability effect is that it does not explain the interaction of Go probability with discriminability. If discriminated perceptual codes for color and shape were simultaneously made available to the decision process, the effect of shape should be independent of the difficulty of the perceptual discrimination, because this discrimination would already have finished.

In defense of the discrete model, one might reply to the second argument that perhaps the perceptual output depends on the difficulty of the discrimination, so that the decision process has to do more work to determine the response when the perceptual discrimination is difficult than when it is easy. This is a weak reply, however. If the decision process categorizes stimuli based on relatively unprocessed perceptual information, what does the perceptual process do? In essence, this defense of a discrete model tries to circumvent the problem of preliminary output by including both perceptual analysis and decision processes within a single stage. One cannot rule out such an explanation, of course. In the limit, a discrete theorist can put all processing within a single stage, and then there can be no possibility of disproving the model by finding evidence of preliminary output from one stage to the next. But such a theoretical maneuver throws out the baby with the bathwater, since discrete stage modeling is only powerful to the extent that multiple stages can be identified. The maneuver is particularly unreasonable in the present case, because it denies the well-accepted distinction between perceptual information accumulation and decision-level determination of arbitrary S–R assignments. It seems clear from the present results that categorized information about letter name has an effect before the categorization of color has finished, and the pre- versus post-categorization boundary provides a very natural dividing line between stages.

Table 2
Stimulus probabilities for a sample subject in experiment 3.

	Imperative attribute			
	Green/Go (Inducing	Blue/Go (Test)	Purple/No-go	Orange/No-go
Cuing attribute				
S	0.425	0.025	0.025	0.025
T	0.025	0.025	0.025	0.425

The second possible explanation of the Go probability effect within a discrete model attributes the effect to a criterion adjustment that occurs entirely within the perceptual process. Note that in experiment 2, because of the stimulus probabilities used, letter name predicted not only the decision (i.e., Go probability) but also the color of the stimulus. Perhaps, due to perceptual learning, letters acquire the ability to alter the perceptual criteria for colors that they predict, with the criterion being reduced for a more probable color rather than a more probable response. This would lead to faster perception of an expected than an unexpected color, so the Go probability effect could actually have arisen within perceptual processing. Indeed, this explanation is quite compatible with the finding that the Go probability effect is larger when the discriminability of the imperative attribute is reduced.

The explanation in terms of perceptual preparation must be ruled out if the Go probability effect is to be used as an index of decision-level adjustment. If cuing information only causes preparation within the perceptual process, then the Go probability effect certainly does not demonstrate that post-perceptual processing can begin before perception finishes.

The purpose of experiment 3 was to test the perceptual versus post-perceptual adjustment explanations of the Go probability effect. These explanations can be separated by assigning two colors to each response (Go vs. No-go) and manipulating probabilities separately for different colors, as shown in table 2.

Overall cuing probabilities were the same as those used in experiment 2. For the sample subject shown in table 2, the Go response is made 90% of the time that an S is presented and only 10% of the time that a T is presented. Thus, the letter S indicates that the Go response has high probability and the letter T indicates that it has low probability.

In this design, however, the effect of Go probability can be measured separately for the two different Go colors. One Go color (the 'inducing' color) occurs much more often with the S than with the T, and it is the many S's in this color that create the higher probability of a Go response for S than for T. The other Go color (the 'test' color) occurs equally often with the S and T.

If the Go probability effect observed in experiment 2 was a post-perceptual effect, then a similar effect should be found in this design for both the inducing color and the test color. That is, responses should be faster to S's than T's in the inducing color, and also in the test color. According to the post-perceptual explanation, letter name influences the readiness for the Go response before color information is available. This readiness change should influence responses to stimuli in both the inducing and test colors.

If the Go probability effect of experiment 2 was due to perceptual preparation, however, the analogous effect in this design should be observed only for stimuli in the inducing color, not for stimuli in the test color. By the perceptual preparation hypothesis, the perceptual system uses letter name to prepare itself for each color in proportion to the probability of that color being present. Thus, the perceptual system should be more prepared for the inducing color when an S is presented than when a T is presented, because the probability of the inducing color is higher in the former case. However, the perceptual system should be equally prepared for the test color regardless of which letter is presented, because the probability of the test color is equal for the two letters. Thus, a perceptual advantage for Go stimuli should be found for the inducing color but not the test color.

Method

This experiment was very similar to experiment 2, with the exception of the colors used. All blocks of trials used four colors: blue, green, purple, and orange. In each block of 120 trials one letter was presented 51 times in the inducing Go color and three times in each of the other colors. This letter, then, cued a high probability of a Go response. The other letter was presented 51 times in the inducing No-go color and three times in each of the other colors, so it cued a low probability of a Go response. The assignments of colors to inducing, test, and No-go conditions were counterbalanced across subjects, as was the use of S versus T to cue high probability of a Go response. A new group of 64 subjects was tested.

Results and Discussion

Fig. 4 shows average RT as a function of Go probability for both inducing and test colors. Responses were 50 ms faster to the inducing color than the test color, $F(1,63) = 28.134$, $MSE = 5833.8$, $p < 0.001$, and 42 ms faster for the letter indicating high as opposed to low Go probability, $F(1,63) = 54.462$, $MSE = 2157.0$, $p < 0.001$. The interaction between these two factors was also significant, $F(1,63) = 29.028$, $MSE = 1951.4$, $p < 0.001$. In addition, a separate analysis including only the test color showed that the 13 ms Go probability effect in this condition was significant, $F(1,63) = 4.5763$, $MSE = 1198.8$, $p < 0.05$.

There were fewer than 1% errors of omission, and there were no significant effects on these errors. On the other hand, there were about 5.8% false alarms. The proportion of false alarms was higher for the low probability No-go color (9.6%) than for the high probability No-go color (2%), $F(1,63) = 27.3$, $MSE = 543.8$, $p < 0.001$, and it was higher when the letter name signalled high Go probability (7.1%) than when it signalled low Go probability (4.4%), $F(1,63) = 9.46$, $MSE = 173.0$, $p < 0.005$. False alarms also decreased across blocks from 8.5% to 4.5%, $F(3,189) = 4.5368$, $MSE = 19787.1$, $p < 0.005$.

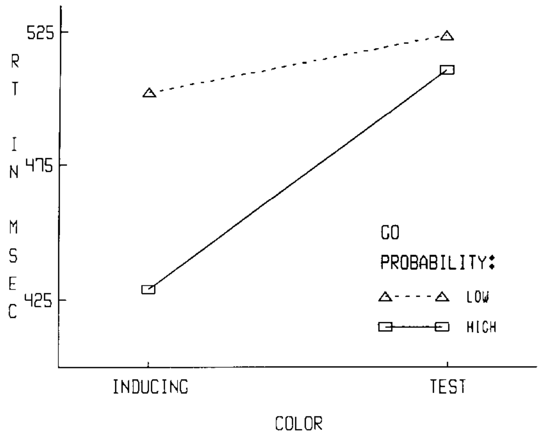

Fig. 4. Experiment 3. Reaction time (RT) as a function of (a) color indicating the Go response, and (b) probability of a Go response given the letter name.

The finding of a Go probability effect on RT even with the test color is strong support for the claim that the effect arises because of a post-perceptual adjustment rather than a perceptual one. The test color occurs equally often with the letters indicating high and low probability of a Go response, so perceptual preparation for this color should have been independent of letter identity. Nonetheless, responses to the test color were significantly faster when the letter indicated high rather than low Go probability. Thus, information about Go probability, provided by letter identity, must have influenced processing in a manner that generalized across all stimulus colors assigned to the Go response. Such generalization would not be expected without transfer of preliminary information out of the perceptual system and at least up to the decision level at which arbitrary response assignments are represented.

It is not surprising that responses were faster overall to the inducing color than the test color, because the former color was presented nine times as often as the latter. Subjects may therefore have more quickly recognized it or retrieved the response with which it was associated.

More interesting is the large interaction of Go probability and inducing versus test color (see fig. 4). Specifically, almost all of the advantage for the inducing color over the test color occurred with the letter indicating high rather than low Go probability. This interaction can be explained in terms of the high probability of the particular conjunction of the inducing color with the letter indicating high Go probability. This conjunction occurred on 42.5% of all trials, whereas the other three conjunctions each occurred on 2.5% of all trials. Thus, the high probability of this particular conjunction may have speeded responses to this stimulus item relative to the other ones.

There is an interesting theoretical implication of the view that conjunction probability is the explanation of the interaction in fig. 4. It follows that the representation of a conjunction stimulus is not simply the amalgamation of two separate attributes (cf. Miller 1991). For example, one might entertain a model in which there are independent sets of logogens for all of the different stimulus dimensions (e.g., shape, color), and a conjunction is represented merely by turning on one logogen along each dimension. On this model, however, it is not clear why there should be a special advantage for a high probability conjunction of attributes. To explain the conjunction-specific advantage, it seems necessary to postulate either special representations for conjunctions or else cross-dimensional interactions that depend on attribute cooccurrence probabilities.

In summary, the results of experiments 1–3 support two main conclusions with respect to the issue of discrete versus continuous models. First, preliminary information about a stimulus is sometimes transmitted to later processes before recognition of that stimulus is finished. Previous experiments have demonstrated effects of preliminary information about response-relevant attributes (e.g., Coles and Gratton 1986; Miller 1982a). The current paradigm extends this work by providing evidence that information about irrelevant attributes can also have an effect. Second, the effects of stimulus probability in this paradigm cannot be ignored. Probability can have an effect even when it varies on a response-irrelevant attribute. Therefore, it is essential to include stimulus probability control conditions in paradigms attempting to demonstrate post-perceptual effects in this task.

Experiment 4. Letters varying in name (cuing attribute) and size (imperative attribute): Two alternative sizes

From the results of experiments 2 and 3, it would appear that the present Go versus No-go paradigm might be an extremely simple and therefore highly useful means of determining when the perceptual system transmits preliminary information about attributes recognized early in stimulus analysis. In attempting to replicate the results with a slightly different set of attributes, however, we discovered that the paradigm is not as simple as it looks. Experiments 4 and 5 report the results obtained with these replications.

The stimuli in question are large and small S's and T's like those used in previous research investigating the discreteness or continuity of information transmission (Miller 1982a, 1983, 1987a; Miller and Hackley 1990). These stimuli are exactly analogous to those of experiment 2, except that size replaces color as the imperative stimulus attribute. Pilot work indicated that letter name is recognized before size, and we sought to find out whether letter name would influence response readiness before size discrimination was complete. To do this, letter name indicated the probability of a Go response, exactly as in experiment 2.

Method

This experiment was an exact replication of experiment 2 except that the imperative dimension was size instead of color. In the condition with an easy size discrimination, large and small letters were approximately 1.81 and 0.96 degrees of visual angle in height, respectively, with the same height to width ratio as in the previous experiments. In the condition with a difficult size discrimination, large and small letters were approximately 1.19 and 1.53 degrees in height. Forty-eight subjects were tested in the response preparation condition, and an additional 24 were tested in the stimulus probability control condition.

Results and Discussion

Fig. 5 shows the results from the experimental condition. Responses were 49 ms faster with the letter cuing high Go probability than with the letter cuing low Go probability, $F(1,46) = 46.174$, MSE = 2575.1, $p < 0.001$, and they were 101 ms faster with the difficult size discrimination than with the easy one, $F(1,46) = 62.653$, MSE = 7792.6, $p < 0.001$. Furthermore, the Go probability effect was larger with the difficult discrimination (64 ms) than with the easy one (36 ms), $F(1,46) = 5.6303$, MSE = 1666.0, $p < 0.025$.

There were 1.7% errors of omission when the discrimination was difficult, versus 0.6% when it was easy, $F(1,46) = 9.68$, MSE = 6.03, $p < 0.005$, with no other significant effects on this measure. False alarms were more common when the discrimination was difficult (5.5%) than when it was easy (1.1%), $F(1,46) = 30.3$, MSE = 31, $p < 0.001$. They were also more common for high (4.8%) than low (1.8%) Go probability, $F(1,46) = 14.94$, MSE = 29.78, $p < 0.001$, especially when the discrimination was difficult, $F(1,46) = 6.9$, MSE = 17, $p < 0.025$.

The results from the experimental condition are completely consistent with the hypothesis that preliminary information about letter name is used to adjust response readiness before the size discrimination is made. Responses were faster and there were more false alarms when the letter name predicted the Go response than when it predicted the No-go response, and these effects were larger for the more difficult size discrimination.

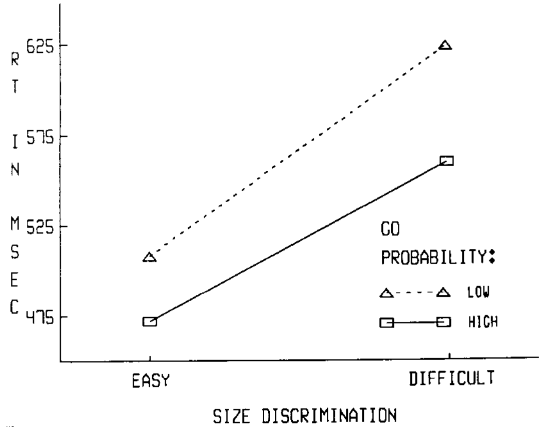

Fig. 5. Experiment 5. Reaction time (RT) as a function of (a) difficulty of the size discrimination, and (b) probability of a Go response given the letter name.

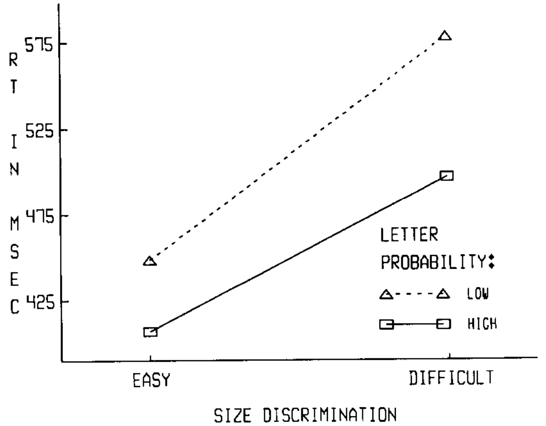

Fig. 6. Experiment 5 (probability control condition). Reaction time (RT) as a function of (a) difficulty of the size discrimination, and (b) probability of the letter name.

However, the results from the stimulus probability control condition, shown in fig. 6, suggest that the results of the experimental condition may be explainable entirely in terms of simple probability effects, without reference to readiness changes. Responses were 61 ms faster to high than low probability letters, $F(1,22) = 40.051$, MSE = 2226.7, $p < 0.001$, and the effect of discriminability was 109 ms, $F(1,22) = 104.63$, MSE = 2723.3, $p < 0.001$. Furthermore, the effect of probability was clearly larger with the difficult (81 ms) than with the easy (41 ms) size discrimination, $F(1,22) = 6.8661$, MSE = 1398.2, $p < 0.02$. There were again slightly more errors of omission when the discrimination was difficult (1.9%) than when it was easy (0.1%), $F(1,22) = 4.26$, MSE = 18.97, $p < 0.06$. False alarms were more common when the discrimination was difficult (7.7%) than when it was easy (1.8%), $F(1,22) = 18.3$, MSE = 45.95, $p < 0.001$, and more common when letter probability was low (6.5%) than when it was high (3.0%), $F(1,22) = 4.46$, MSE = 66.54, $p < 0.05$. As in the experimental condition, the probability effect on false alarms was larger when the discrimination was difficult (5.4%) than when it was easy (1.6%), but this difference did not approach statistical significance, $F(1,22) = 2.21$, MSE = 38.44, $p > 0.15$.

In combination, the results of the experimental and control conditions do not support the view that letter name is used to adjust readiness for a Go response before the size discrimination is made. Instead, the results are consistent with the view that the Go probability effect is simply one of stimulus probability.

Two considerations suggest, however, that the present criterion for preliminary output (namely, larger Go probability effect in experimental condition than simple probability effect in control condition) may be inappropriate with these stimuli. One is in the present data: the effect of probability is very large in the stimulus probability control condition. Whereas probability had a 21 ms effect in the control condition of experiment 2, it had a 70 ms effect in that of the present experiment. These two experiments were identical except for the change from color to size as the imperative stimulus dimension. The fact that irrelevant name probability had a much larger effect with the latter imperative dimension suggests the possibility of an unanticipated artifact.

The second consideration is that previous data strongly suggest letter name is transmitted by the perceptual process before the size discrimination is finished. Evidence from several other paradigms using exactly these same stimuli suggests letter name is used for response preparation (Miller 1982a, 1983, 1987a; Miller and Hackley 1990), and letter name was used to adjust response readiness in experiment 2, albeit during a discrimination on color rather than size.

What might be wrong with the present criterion for preliminary output with these stimuli? One possibility is that the expected adjustment of response readiness takes place, as suggested by the results in fig. 5, but that some other factor exaggerated the probability effect in the control condition. If preliminary output is inferred only from the excess of the Go probability effect over the simple probability effect in the control condition, any additional factor that contributed to the simple probability effect would tend to conceal the existence of such output.

We believe that such a factor is operating in experiment 4: letter-specific discrimination practice. With these stimuli, we hypothesize, the size discrimination is so highly form-dependent that the discrimination can be made more rapidly for letters seen frequently (much practice) than for letters seen infrequently (little practice).

If size discrimination is highly form-dependent, then differential practice with the different letters would have contaminated the results. Consider first the experimental condition. As has already been discussed, two factors could contribute to the comparison used in defining the Go probability effect (i.e., Go stimuli with letter name cuing high vs. low Go probability): response-readiness adjustment, and individual stimulus probability. Letter-specific discrimination practice could not contribute to the Go probability effect, though, because half of the stimuli were S's and half were T's (i.e., subjects got equal amounts of practice at making the size discrimination for S's and T's).

In the stimulus probability control condition, on the other hand, 90% of the stimuli had one letter name and the other 10% had the other letter name. Thus, subjects got much more practice at discriminating small from large for the high probability letter than for the low probability one. Perhaps it is easier to discriminate small from large S's when many S's are presented than when only a few are, and likewise for T's. The probability effect in this condition therefore reflects not only the effect of individual stimulus probability but also the effect of letter-specific discrimination practice (total number of stimuli with that letter name).

In short, the experimental and stimulus probability control conditions differ not only with respect to the cuing of response probability by letter name, but also with respect to the amount of letter-specific practice with the size discrimination. If letter-specific practice has a larger effect than readiness adjustment, then the effect of probability would be larger in the control condition than in the experimental condition. If it were the same size, equivalent effects would be found in the two conditions.

The data provide some support for the view that letter-specific practice is responsible for the lack of evidence for adjustment of response readiness obtained with stimuli varying in letter name and size. One piece of evidence is the larger effect of letter probability in the control condition of experiment 4 than in that of experiment 2. This seems to be clear evidence that letter-specific practice has a larger effect on size discriminations than on color discriminations, given that letter identity is irrelevant in both cases. Another piece of evidence is provided by an analysis of sequential effects, which will be presented after experiment 7. One might expect that a third piece of evidence would be provided by examining changes in the effects with practice, but this is not necessarily so. As long as the cuing and letter-specific practice effects develop at the same rate across trials, their relative sizes might remain more or less constant throughout the experiment. In any case, the strongest support for this hypothesis would come from a demonstration of response readiness adjustment when the confounding effect of letter-specific practice is removed, and that demonstration is provided by the next experiment.

Experiment 5. Letters varying in name (cuing attribute) and size (imperative attribute): Four alternative sizes

If letter-specific size discrimination inflated the probability effect in the control condition, thereby concealing the effect of response-readiness adjustment, then it should be possible to uncover this effect using a version of the four-color paradigm used in experiment 3 (see table 2). In this paradigm each stimulus letter is presented equally often, so the subject has equal practice at making discriminations with each letter. Furthermore, the critical comparison is between responses to two Go stimuli with equal probability, so it is unnecessary to run the control condition in which the probability effect was allegedly exaggerated in experiment 4.

The present experiment was an exact analog of experiment 3, except that the S's and T's appeared in four sizes rather than in four colors. The heights of the letters were approximately in the ratio of 1 : 2 : 3 : 4.

To describe the S–R assignments and probability manipulations, it is helpful to define the four sizes as constituting two pairs: the two smaller being one pair and the two larger being the other pair. For each subject, one of the two Go sizes came from each pair. This constraint was used so that subjects would have to discriminate among all four sizes rather than simply discriminating the two smallest from the two largest, as could be done if two members of the same pair were assigned to the same response. One size pair was then selected for the probability manipulation (the inducing pair), and the other size pair was used as the test pair.

One subject, for example, had to respond to letters of sizes 1 and 3, withholding the response to letters of sizes 2 and 4. This subject might see 42.5% S's of size 1, 42.5% T's of size 2, and 2.5% of each of the other six letter/size combinations (cf. table 2). The smaller pair would then be the inducing pair, and the letter S would be correlated with, and therefore cue, the Go response. The critical test for response preparation would occur with letters of size 3, the Go size from the test pair. If S's increase response readiness and T's decrease it, then there should be faster responses to S's of size 3 than T's of size 3.

Method

This experiment was an exact replication of experiment 3 except that the imperative dimension was size instead of color. The four different letter heights were about 0.57, 1.19, 1.81, and 2.48 degrees of visual angle, with the same height to width ratio as in the previous experiments. Forty-eight subjects were tested. Assignments of sizes to responses and probability conditions were fully counterbalanced within the constraints described above.

Results and Discussion

The results are shown in fig. 7, averaged across the four blocks of practice. Responses were 125 ms faster for the inducing size than the test size, $F(1,47) = 26.651$, MSE = 28240.0, $p < 0.001$, and 95 ms faster for the letter indicating high as opposed to low Go probability, $F(1,47) = 54.667$, MSE = 7901.8, $p < 0.001$, with a highly significant interaction between these factors, $F(1,47) = 16.340$, MSE = 7807.0, $p < 0.001$. A separate analysis showed that the 43 ms Go probability effect was significant considering only the data from the test size, $F(1,47) = 5.1744$, MSE = 8701.2, $p < 0.05$.

There were about 5.5% errors of omission overall. These were more common to letters of the test size (6.9%) than to letters of the inducing size (4.0%), $F(1,47) = 7.4284$, MSE = 54.65, $p < 0.01$, and more common with low (6.3%) than high (4.5%) Go probability, $F(1,47) = 7.1147$, MSE = 23.51, $p < 0.02$.

False alarms were quite common overall (14.7%). They were more common for the low probability No-go size (22.4%) than for the high probability No-go size (7.0%), $F(1,47) = 29.27$, MSE = 1,548, $p < 0.001$, and more common when Go probability was high (17.2%) than when it was low (12.2%), $F(1,47) = 8.67$, MSE = 541.45, $p < 0.01$.

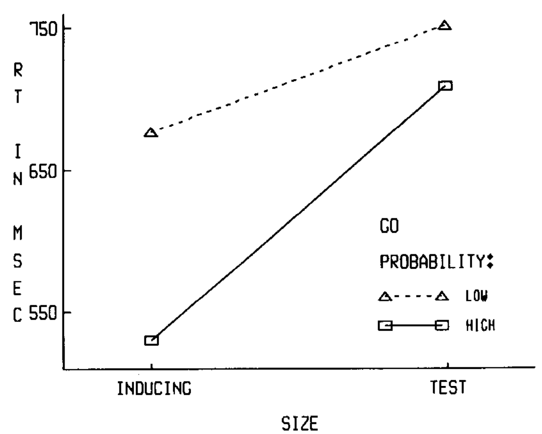

Fig. 7. Experiment 6. Reaction time (RT) as a function of (a) size indicating the Go response, and (b) probability of a Go response given the letter name.

Furthermore, these two factors interacted, with the effect of size probability being nearly twice as large when Go probability was high as when it was low, $F(1,47) = 11.26$, MSE = 417, $p < 0.005$. The percentage of false alarms also decreased by about 11% across the four blocks of practice, $F(3,141) = 10.6$, MSE = 399, $p < 0.001$.

The main result of this experiment is the significant Go probability effect on RT for letters of the test size. This result supports the hypothesis that preliminary information about letter name can be used to adjust response readiness before stimulus size has been determined, consistent with previous findings concerning these stimulus dimensions and consistent with the findings of experiments 2 and 3 using the dimensions of letter name and color.

The results also support the hypothesis that letter-specific practice was responsible for the failure to find evidence of preliminary output in experiment 4. For one thing, the appearance of the Go probability effect, controlling for stimulus probability, is predictable from that hypothesis, because letter-specific practice is not a confounding factor in this paradigm. For another, the strong interaction of Go probability and inducing versus test stimulus (see fig. 7) suggests that item probability is an especially potent variable with these stimuli. The Go probability effect was much larger for the inducing size than the test size, but the effects of readiness adjustment based on preliminary letter name should have been the same in the two cases (i.e., because size has not yet been determined at the point when this effect is being produced). Thus, the larger effect for the inducing size must be attributable to some other factor, most likely the especially high stimulus probability (42.5%) of the inducing letter with high Go probability. Because there is a strong effect of the probability of a particular combination of letter name and size, it is likely that there would also be a strong effect of the marginal probability of a given letter name (i.e., letter-specific practice effect).

Experiment 6. Letters varying in name (cuing attribute) and size (imperative attribute): Divided attention task

The Go probability effect observed in experiments 2–5 indicates that preliminary information about letter name can be used to adjust response readiness before perceptual analysis has finished, and the transfer of the effect to the test colors (experiment 3) and sizes (experiment 5) indicates that it is a post-perceptual rather than a perceptual effect. There are two obvious possibilities for the post-perceptual locus of this effect.

One is that it is produced by adjustments in decision criteria. The concept that decisions are made by comparing incoming information against an internal criterion is well-accepted not only in models of perceptual judgments (e.g., Green and Swets 1966), but also in models of stochastic decision-making (e.g., Edwards 1965; Luce 1986). In any rational statistical decision maker, information indicating that the Go response had high probability would count as evidence for that response, and thereby effectively reduce the amount of stimulus information needed to select that response (i.e., reduce the criterion for that response). This would speed Go responses, when they were appropriate, as observed. If there were some noise in the decision process, it would also produce some false alarms when No-go responses were appropriate. Conversely, information indicating that the Go response had low probability would be expected to increase the criterion for making that response, thereby slowing Go responses and perhaps causing some Go responses to be omitted.

A second possibility is that the effect of Go probability is produced by motor adjustments peripheral to the decision stage. According to this explanation, a cue indicating high Go probability causes the motor system to enter a highly activated state from which the response can be executed especially quickly, once the decision to respond has been reached. Perhaps some false alarms would also occur if preparation pushed the motor activation across a critical threshold (Näätänen and Merisalo 1977). When the cue indicated low Go probability, the motor system would become relatively less activated, so it would take longer to execute the response if the decision to Go were reached.

To test between these two explanations, this experiment used a divided attention version of experiment 4. As in experiment 4, subjects had to respond to either small letters or large letters, and letter name was correlated with the response. In addition, however, subjects had to respond whenever a tone sounded.

The critical comparison involves responses on trials with a letter of the No-go size plus a tone (cf. Miller 1985, 1987a). Subjects must respond, because of the tone, but the question is whether their RTs will be influenced by the name of the letter. According to the motor activation hypothesis, the motor system enters a state of higher readiness when letter name indicates that Go probability is high rather than low. This increased readiness should facilitate responses to the tones, even when the size of the letter indicates that the No-go response should be made.

On the other hand, if the Go probability effect results from a decision-level adjustment, then responses to tones need not be affected by the name of the No-go letter. This prediction follows immediately if it is assumed that separate decision criteria are maintained for the visual and auditory Go signals, because then the change in criterion produced by letter name would not have any impact on the processing of tones. Even without this assumption, though, the prediction seems valid as long as the tones are highly salient. The Go probability effect decreases as discriminability increases (experiments 2 and 4), as would be expected since the former affects a criterion and the latter influences the rate of information accumulation. Salient tones are extremely discriminable, compared to the alternative of no tone. With such high discriminability, it seems plausible that the rate of information accumulation would be so great that changing the criterion would have a negligible effect.

Size discriminability was not varied in this experiment. In order to study the Go probability effect at its largest, only the harder size discrimination from experiment 4 was used.

Method

Forty-eight subjects were tested in an experiment identical to experiment 4, except for changes necessitated by the addition of tones. Within each of the four blocks of trials, exactly half of the trials with each of the four visual stimuli also had a tone. The computer's speaker generated a tone at 800 Hz, with a loudness of about 75 db, starting 200 ms after the onset of the letter. Because a tone was recognized faster than a letter, it was necessary to delay the tone slightly to make sure that letter name had a chance to be recognized and have an effect. On the other hand, it was desirable to keep the delay short enough that the tone would occur before the size discrimination had been made, to look for possible effects of response preparation based on partial information. Subjects were instructed to respond with the same response key to either a visual Go stimulus or the tone, and the instructions emphasized equally the importance of fast responses in either case.

Results and Discussion

Table 3 presents average results as a function of stimulus condition. The tone-absent trials produced a 40 ms effect of Go probability, $F(1,47) = 10.463$, MSE = 3605.4, $p < 0.005$. The main effect was somewhat smaller than that observed with the hard discrimination in experiment 4, but additional analyses indicated that it increased across blocks, suggesting that the presence of tones interfered somewhat with learning the correlation between letter name and response.

On redundant signal trials (i.e., both tones and letters indicated the Go response), responses were 14 ms faster when letter name indicated high (363) than low (377) Go probability, $F(1,47) = 14.309$, MSE = 1358.4, $p < 0.001$. This indicates that the tones were delayed enough so that responses could be influenced by the letters as well as the tones. On the other hand, the substantial advantage of the conditions with both tone and Go letter (i.e., 363 and 377) over the conditions with just a Go letter (i.e., 509 and 549) indicates that the tone was early enough to have a major impact on responding. Responses on these trials also speeded up by over 100 ms across the four blocks of practice, $F(3,141) = 64.508$, MSE = 8531.5, $p < 0.001$.

Table 3
Mean reaction time (RT), percentage errors of omission (% O) and percentage false alarms (% FA) as a function of stimulus condition for experiment 6.

Stimulus Condition			Performance		
Letter name	Letter size	Tone	RT	% O	% FA
High Go probability	Go	Absent	509	1.3	
Low Go probability	Go	Absent	549	1.9	
High Go probability	No-go	Absent			20.6
Low Go probability	No-go	Absent			12.3
High Go probability	Go	Present	363	0.0	
Low Go probability	Go	Present	377	0.1	
High Go probability	No-go	Present	392	0.5	
Low Go probability	No-go	Present	380	0.3	

The effect of Go probability on trials with redundant signals can be interpreted as a coactivation effect (Miller 1982b), with both signals contributing towards the activation needed to make the response. Responses are faster to letters signalling high than low Go probability, so the former letters should also contribute more activation to be combined with that produced by the tone. It is perhaps surprising that these letters could contribute anything, given that responses to them were so much slower than responses to tones. However, there is previous evidence that response activation is sufficiently time-consuming that signals perceived later can influence responses mainly evoked by signals perceived earlier (Miller 1986).

The crucial test for the motor activation hypothesis is the comparison of responses to high and low Go probability letters in the No-go size, with tones present to demand the response. On average across blocks, there was a significant 12 ms effect in the wrong direction, $F(1,47) = 5.3019$, $\mathrm{MSE} = 2740.3$, $p < 0.05$, with faster responses to tones presented with the letter indicating low rather than high Go probability. This reversal decreased steadily across blocks of practice, however, leading to a significant block by Go probability interaction, $F(3,141) = 4.9621$, $\mathrm{MSE} = 3576.3$, $p < 0.005$. In fact, by the last block there was an effect of 12 ms in the expected direction, although this did not approach significance, $F(1,47) = 1.6154$, $\mathrm{MSE} = 2290.5$, $p > 0.20$. There was also a main effect of blocks, $F(3,141) = 5.1947$, $\mathrm{MSE} = 8488.3$, $p < 0.005$, with responses on these trials speeding up about 50 ms over the course of the four blocks.

Responses to tones combined with No-go letters do not support the hypothesis that motor activation is responsible for the Go probability effect. If anything, it seems that motor activation was reduced by a letter indicating high Go probability, at least in the first part of the experiment. Perhaps this reduction is a consequence of trying to avoid the false alarms which are quite likely with these stimuli. In any case, it seems reasonable to conclude that the Go probability effect with letters varying in size results from adjustment in the decision stage rather than motor activation.

It would be possible to argue that the present experiment was not a fair test of the motor activation hypothesis, because the tones were delayed so long that this activation dissipated before the tone arrived. This argument seems very unlikely in view of the results of Miller (1987a), who found that motor activation lasted several hundred milliseconds once it had been established. The converse argument, that the tones were not delayed enough for the effect to develop, is ruled out by the Go probability effect on trials with redundant signals (i.e., tone plus letter presented in the Go size).

It is very interesting to contrast the transfer of the Go probability effect in experiments 3 and 5, from inducing to test stimulus, with the lack of transfer in experiment 6, from inducing stimulus to auditory probe. Why does the effect transfer in one case but not the other? We suggest that the most likely reason is that the preliminary information causes adjustment in the decision criterion *for the stimulus from which it comes*. The test stimuli of experiments 3 and 5 conveyed the preliminary information themselves, and so they would be influenced by the criterion adjustment. But the auditory probes of experiment 6, though recognized at about the same time as the biasing preliminary information, did not themselves convey it. Thus, a stimulus-specific bias would be consistent with the transfer in the former experiment but not the latter.

Experiment 7. Visually similar letters

The results of experiments 2–6 indicate that partial information about letter name is used to adjust response readiness while a more difficult color or size discrimination is being made. This conclusion rules out models with fully discrete transmission, because in these models no information is transmitted out of the perceptual system until perceptual analysis of the stimulus is complete.

The results are compatible with transmission either of arbitrarily small units of information, as in models with continuous transmission, or of discrete attributes, as in the ADC model. According to models with continuous transmission, any information available early in the perceptual analysis of a stimulus is immediately transmitted to later processes, so readiness adjustment should occur whenever any type of early information predicts the response. According to the ADC model, however, early perceptual information is only transmitted if it fully specifies a unique perceptual attribute for which a mental representation already exists. Early information about letter name certainly satisfies this condition, because letter names are highly overlearned entities for which distinct mental representations are available. Other, more arbitrary types of early perceptual information would not satisfy it, however. For example, early information that something was either an apple or a car would not be transmitted to later processes, because there is no distinct mental representation for the disjunctive concept 'apple or car'.

To distinguish between the ADC model and models with fully continuous transmission, it is necessary to use a stimulus set in which the information provided by the easy discrimination does not correspond to any distinct attribute or mental code. This information could then be used to cue the probability of the Go response, but a more difficult discrimination could be required to determine whether the response was actually to be made. Following Miller (1982a), we used sets of visually similar letters like U, V, M, and N. The easy perceptual discrimination indicates to which similar pair a stimulus letter belongs (UV or MN), just as letter name quickly indicated which of two stimulus pairs (S's or T's) had been presented in experiments 2 and 4. However, while a distinct mental representation is activated by letter name (e.g., 'S'), no such representation is activated by the information that a stimulus letter belongs to a certain visually similar pair (e.g., is a U or a V). The more difficult perceptual discrimination indicates exactly which letter of the indicated pair was presented, analogous to the slower color discrimination in the previous experiments.

As in the previous experiments, the easy perceptual discrimination was not sufficient to determine the response. Thus, U and V were assigned to opposite responses, as were M and N. The easy perceptual discrimination did, however, indicate the probability of a Go response. For example, if U and M were the Go letters, U and N might each occur on 45% of the trials, with V and M occurring on only 5% each. In this example, preliminary information that the stimulus is either U or V should in principle bias the system toward the Go response, because that response has a high probability given the preliminary information. Similarly, preliminary information that the stimulus is either M or N should create a bias toward the No-go response, for the same reason.

According to continuous models, any preliminary partial information available to the perceptual system is immediately transmitted to later stages where it is used for post-perceptual processing. Thus, response readiness adjustment should occur as soon as the easy perceptual discrimination had determined which letter pair was represented by the stimulus. This adjustment should increase readiness for the Go response when preliminary information indicates the presence of a letter from the pair with high Go probability (U or V in the above example), and decrease it for the other pair (M or N). Therefore, continuous models predict that responses to U should be faster than those to M, because of the readiness adjustment based on preliminary perceptual information. In fact we estimate that more than 100 ms should be available for such readiness adjustment, based on pilot studies showing that within-pair discriminations (e.g., U vs. V) take about 112 ms longer than between-pair discriminations (e.g., U vs. M).

The ADC model, on the other hand, predicts that preliminary information should not cause readiness adjustment with these stimuli, because there are no previously existing mental codes to represent disjunctive letter categories like 'U or V' or 'M or N'. Without a code to use in transmitting partial information, this information cannot leave the perceptual system before the full stimulus is recognized. Readiness adjustment cannot occur, because the information that would support it is locked within the perceptual system.

As in experiments 2 and 4, it is important to include a control for simple stimulus probability. The Go probability effect is measured using two letters that are presented unequally often, so a simple effect of stimulus probability would qualitatively mimic that of readiness adjustment. Thus, the operational definition of readiness adjustment must be whether the Go probability effect is larger than that attributable to stimulus probability alone.

Method

This experiment was modeled after experiments 2 and 4, except for the change in stimulus sets. There were three different letter sets: CGKR, OQEF, and UVMN. Each of 48 subjects was tested with one of these letter sets for all four blocks of trials. For each subject, one letter from each similar letter pair was assigned to the Go response and the other to the No-go response. One similar pair was selected as the pair indicating a high probability of a Go response, and the Go letter from this pair was presented 72 times per block whereas the No-go letter from this pair was presented only 8 times per block. The other pair then indicated a low Go probability, with its Go letter being presented 8 times and its No-go letter being presented 72 times. For example, one subject responded to C and K, and saw 72 C's, 8 G's, 8 K's, and 72 R's per block.

In the stimulus probability control condition, only the individual letter probabilities were changed. In this condition the probabilities of the two letters within a similar pair were equated, so that preliminary information about the pair did not indicate anything about the probability of a Go response. For example, one subject responded to C and K, and saw 72 C's, 72 G's, 8 K's, and 8 R's per block. A new group of 48 subjects was tested.

Results and Discussion

Responses were 86 ms faster to the Go letter from the pair cuing high Go probability (422 ms) than from the pair cuing low Go probability (508 ms), $F(1,45) = 151.96$, $MSE = 4613.0$, $p < 0.001$, and this effect did not vary as a function of the between-subjects factor of letter set ($F < 1$). This finding is consistent with the hypothesis that preliminary information about letter pair was used by the decision process before complete information was available.

In the stimulus probability control condition, however, almost the same effect was observed: responses were 81 ms faster to the high probability letter than to the low probability letter, $F(1,45) = 165.56$, $MSE = 3855.9$, $p < 0.001$. An analysis comparing the probability effects in the two conditions provided no suggestion that the effect was larger in the experimental condition than in the stimulus probability control, $F(1,90) = 0.17$, $p > 0.20$.

Errors of omission were too few to analyze in either the experimental or stimulus probability control condition, averaging less than 0.5% in each case. In the experimental condition, false alarms were more common for the No-go letter from the pair with high (7.9%) than low (0.8%) Go probability, $F(1,45) = 33.9$, $MSE = 140.9$, $p < 0.001$, and they decreased across blocks, $F(3,135) = 3.15$, $MSE = 43.1$, $p < 0.05$. Similarly, in the stimulus probability control condition, false alarms were more common for the low probability No-go letter (5.5%) than for the high probability No-go letter (1.0%), $F(1,45) = 13.47$, $MSE = 144.4$, $p < 0.002$. Across blocks, there was a decrease in both the overall number of false alarms, $F(3,135) = 9.3$, $MSE = 34.22$, $p < 0.001$, and the effect of probability on false alarms, $F(3,135) = 9.92$, $MSE = 34.11$, $p < 0.001$.

The finding that all of the Go probability effect can be attributed to stimulus probability suggests that preliminary information is not used to adjust response readiness with these stimuli. Had the adjustment occurred, there should have been a larger effect of Go probability in the experimental condition than in the control condition, but there was not. Thus, we tentatively conclude that preliminary information about letter pair membership is not transmitted from the perceptual process to the decision process, consistent with the ADC model.

Although the results support the ADC model rather than continuous models, it is necessary to consider whether an analog of the letter-specific practice confound might have concealed readiness adjustment in experiment 7, as it did with stimuli varying in name and size (experiment 4). For example, in the experimental condition subjects discriminated between E and F on half the trials, while in the stimulus probability control condition they made this discrimination on 90% or 10% of the trials. Thus, any effect of letter-pair-specific discrimination practice (e.g., E from F) would have contributed to the probability effect in the control condition but not to the Go probability effect. It is possible, then, that an effect of letter-pair-specific discrimination practice would have concealed the effects of readiness adjustment in this experiment.

Some evidence against this account of experiment 7 comes from an analysis of sequential effects in these experiments, presented in the next section. However, two other arguments also make this interpretation unlikely. One argument is that it is unlikely that the effects would cancel out exactly, especially given the finding that the confound had a larger effect than Go probability in experiment 4. A second and stronger argument is that there is evidence (Miller 1979) that the perception of a letter is not influenced by the probability of another letter that is visually similar to it. This is direct evidence against the hypothesis that letter-pair-specific discrimination practice accounted for the lack of evidence for readiness adjustment with the visually similar letter pairs of the present experiment 5. If letter-pair-specific discrimination practice were a potent factor with these stimuli, then extra presentations of one member of a visually similar pair should facilitate responses to the other member of the pair (i.e., probability effects should transfer). Such transfer, however, does not occur (Miller 1979).

Another possible explanation for the lack of evidence for readiness adjustment with these stimuli is that subjects never learned the relationship between letter pair and response probabilities. This explanation seems rather ad hoc, however, in that it depends on the arbitrary assumption that a given unit of information can support transmission but not learning. Furthermore, learning of response correlations seems quite automatic and robust (Miller 1987b), so it is not clear why the correlation would not be learned in this case if the information were available. Certainly, the large effect of probability shows that subjects were influenced by the varying simple probabilities, so it is difficult to maintain that response probabilities had no effect here for some reason other than that the information was not transmitted. Perhaps it will turn out with further study that noncodable information supports neither preliminary transmission nor learning of response probabilities; in that case, clearly, it is moot to argue about which factor was responsible for the lack of response preparation in this experiment.

Sequential effects in experiments 2, 4, and 7

Although the Go versus No-go task used in experiments 2, 4, and 7 initially seemed to offer a very simple paradigm in which to study transmission of preliminary stimulus information to the decision process, it is clear that probability and practice effects introduce some serious complications. The original idea was that preliminary information could be inferred if and only if Go probability produced effects too large to be attributed to stimulus probability, but we have already seen one case (experiment 4) where this inferential criterion was too conservative.

In this section we present an analysis indicating that sequential effects can be used as an additional converging operation to check for effects of preliminary information. Sequential effects are simply measures of the influence of the preceding trial on the response to the current trial (e.g., Kornblum 1973), but they seem to be intimately related to trial-to-trial criterion changes of the sort that might be

Table 4
Mean reaction time (RT) to high probability Go stimulus as a function of stimulus presented on preceding trial.

Preceding stimulus	Preceding response	Stimulus set		
		Colored letters (Expt. 2)	Small/large letters (Expt. 4)	Similar letters (Expt. 7)
		Experimental conditions		
High Go prob.	Go	439	502	410
High Go prob.	No-go	463	520	453
Low Go prob.	Go	443	537	440
Low Go prob.	No-go	453	527	429
		Control conditions		
High prob.	Go	469	449	423
High prob.	No-go	476	449	465
Low prob.	Go	479	474	453
Low prob.	No-go	469	475	447

involved in readiness adjustment (e.g., Rabbitt 1981; Treisman and Williams 1984). The present analyses show that the experimental conditions of experiments 2 and 4, but not 7, reveal sequential effects that would be expected if the putative readiness adjustment underwent short-term fluctuations in strength due to the outcome of the previous trial. Thus, these effects can be used as additional diagnostic clues when checking for post-perceptual effects of preliminary perceptual information. In addition, sequential analysis is useful because the letter-specific practice effect, hypothesized to influence the results in experiment 4 only, leaves a distinctive signature in sequential effects.

For each of the different stimulus sets (experiments 2, 4, and 7), average RT to the high probability Go letter was computed as a function of the stimulus presented on the preceding trial. [6] These averages were computed separately for each subject, and the overall averages across subjects are shown in table 4. It should be emphasized that all the RTs for a given subject reflect responses to the same stimulus, so any significant differences are attributable to the influence of the stimulus presented on the previous trial.

[6] The low probability Go letter occurred so infrequently that we could not perform a similar analysis on it.

Context-specific discrimination practice

We will first consider the sequential effects indicative of context-specific discrimination practice. In these experiments subjects were required to make a relatively difficult discrimination (e.g., color, size, U vs. V, M vs. N) on each trial. An easier discrimination could also be made, of course (e.g., S vs. T, UV vs. MN), and this discrimination can be regarded as determining the context (e.g., S or T, UV or MN) in which the more difficult discrimination had to be made.

If context-specific discrimination practice is helpful, responses should be faster when a given trial has the same context as the previous trial rather than a different context. For example, suppose that making the small versus large discrimination for an S helps subsequent small versus large discriminations involving S's more than it helps subsequent discriminations involving T's. This might be the case if the size discriminations were made relative to template-like mental representations of medium sized S's and T's, and if the representation used on the previous trial were especially accessible on the current trial. Then the small versus large discrimination for an S would very likely be faster if the immediately preceding stimulus had also been an S rather than a T, due to a kind of short-term perceptual learning. [7]

It is best to look for this sequential effect in the stimulus probability control conditions of the present experiments. In the experimental conditions, these sequential effects are compounded with additional effects resulting from readiness adjustments, as discussed next.

The sequential effect predicted by context-specific discrimination practice is evident in the control condition of experiment 4 (letters varying in size). Responses were about 25 ms faster when the preceding stimulus had the same name than when it had the other name, $F(1,23) = 21.836$, $MSE = 1458.8$, $p < 0.001$, and this finding held regardless of the preceding response. Thus, the size discrimination could be made faster when the same letter was presented twice in a row than when a different letter was presented on the previous trial, consistent with the claim that the size discrimination is context-specific.

[7] Admittedly, it would be possible to construct perceptual mechanisms in which the effects of practice developed over such a long time that trial to trial repetition effects would be negligible. However, the substantial sequential effects discussed in this section are quite inconsistent with such models.

The control conditions of experiments 2 and 7, on the other hand, show no evidence of context-specific discrimination practice. In experiment 2 (colored letters), RT did not vary as a function of the preceding stimulus, $F(3,93) = 0.82$, $\mathrm{MSE} = 2222.0$, $p > 0.40$, supporting the claim that color judgments are made independently of letter name.

Results from the control condition of experiment 7 also show no evidence of context-specific discrimination practice, thereby providing additional evidence that specific discrimination practice did not provide an important confound concealing preliminary output. In the control condition of experiment 7 (similar letter stimuli), there was a marginally significant overall advantage for repetition of the discrimination context, $F(1,47) = 3.50$, $\mathrm{MSE} = 441.64$, $p < 0.07$, but this was produced only by an exact stimulus repetition, leading to a strong interaction of preceding stimulus pair and preceding response, $F(1,47) = 41.813$, $\mathrm{MSE} = 651.51$, $p < 0.001$. Benefits for exact stimulus repetition are not indicative of context-specific discrimination practice, because they can be explained in terms of a special buffer which holds the last item and its response (e.g., Shiffrin and Schneider 1974). [8] The diagnostic finding is the lack of facilitation following the other stimulus in the same discrimination context (i.e., high Go prob., No-go stimulus). Had there been a strong tendency to perceive one visually similar letter relative to the other one in its pair, there should have been a pair repetition benefit analogous to the letter-name repetition benefit observed in experiment 4. Instead, the pattern of results suggests that these stimuli were perceived as unique entities, with no particular association between visually similar letters (cf. Miller 1979).

In summary, the results of the control conditions support the idea that context-specific discrimination practice is an important factor with letters varying size (experiment 4) but not letters varying in color (experiment 2) or letters varying in similarity (experiment 7), consistent with the conclusions reached in the earlier analyses of overall average RTs.

Readiness adjustment

It is also reasonable to expect certain sequential effects to be produced by the mechanism that adjusts readiness based on pre-

[8] We suspect that item repetition effects were not found in experiment 2 because this 'last-item buffer' is only used with relevant attributes, not irrelevant ones. This makes sense if the buffer is conceived as holding only the mental code used for decision-making on the previous trial.

liminary information. The basic idea is that this mechanism should make a larger adjustment following a trial on which adjustment was beneficial than following a trial on which the adjustment was detrimental. [9] This idea depends on two assumptions, both of which have empirical support: (1) that there are trial-to-trial fluctuations in level of readiness, and (2) that a piece of information which was more helpful on the previous trial will be given more weight on the current trial.

The first assumption (readiness variation) is at the heart of theories of both RT (e.g., Grice et al. 1982b) and sequential effects (e.g., Treisman and Faulkner 1984; Treisman and Williams 1984). In support of this assumption, many variables have been shown to have transient effects on decision criteria, thereby demonstrating the possibility of trial-to-trial fluctuations in readiness at the decision level. These variables include featural similarity (e.g., Estes 1982), location cuing (e.g., Hawkins et al. 1988; Muller and Findlay 1987), warning signal intensity (e.g., Kohfeld 1969), and probability (e.g., Vickers et al. 1977). A finding that is particularly congenial to the assumption of readiness variability in the present instance is that the decision criterion on one trial depends on the identity of the previous stimulus (MacDonald 1976).

The second assumption (i.e., differential weighting) is supported by a variety of evidence that the use of stimulus information depends on its predictive value (e.g., Logan and Zbrodoff 1979). In a focused attention task, for example, the letters in irrelevant locations flanking the target have a larger effect when they are usually response-compatible than when they are usually response-incompatible, suggesting that subjects vary the weight given to information from these flankers (Coles et al. 1991). Similar sorts of differential weighting on a trial-to-trial basis are indicated by analyses of trials following errors (e.g., Donchin et al. 1988).

Sequential dependencies in readiness adjustment should be found especially in the experimental condition, naturally, since only in that condition does preliminary information predict the response. The question is, How would these dependencies affect RTs to Go stimuli from

[9] Obviously, a dependence of readiness adjustments on stimulus sequence would suggest that the mechanism producing these adjustments is not simply a function of probability, but also heavily dependent on the relationships between successive trials. Further research may clarify the extent to which probability and sequence are separately or jointly responsible for inducing preparatory adjustments.

the stimulus pair with high Go probability (i.e., the RTs shown in table 4). [10]

The most straight-forward prediction is that responses should be faster when the preceding trial had the Go stimulus from the pair with High Go probability than when the preceding trial had the No-go stimulus from the same pair. In both these cases, the preliminary information on the previous trial indicated a stimulus from the pair with high Go probability, and this is the same as the preliminary information on the current trial (e.g., both the previous and the current trial were S's). If that previous trial was indeed a Go trial, then the preliminary information was beneficial (i.e., got the system ready to make a Go response which was made). When preliminary information again indicates high Go probability on the current trial, the system should make a fairly large adjustment in response to this information, and the Go response should be made relatively rapidly. If that previous trial was actually a No-go trial, however, then the preliminary information was detrimental (i.e., got the system ready to make a Go response which was not made). In this case, when the same preliminary information arrives on the current trial, the system should resist using it, and the Go response should be made relatively slowly. [11]

The top two lines of table 4 show that responses to the Go stimulus from the pair with high Go probability were indeed faster following a trial with the Go stimulus from this pair than with the No-go stimulus from this pair ($p < 0.05$ in each case). These differences could also have been produced by a benefit for exact stimulus repetition, however, because the comparison pits an exact stimulus repetition against a non-repetition. Fortunately, the data from the control condition may

[10] One could make symmetric predictions about how sequential dependencies would affect No-go trials, but these cannot be measured on RT, and false alarms were not frequent enough in these experiments for the effects to show up in that measure either.

[11] One might also predict faster responses when the preceding trial had the No-go stimulus from the pair with low Go probability than when the preceding trial had the Go stimulus from that same pair. In both these conditions, the preliminary information on the previous trial indicated a stimulus from the pair with low Go probability. If that previous trial was indeed a No-go trial, then the preliminary information was beneficial; if it was a Go trial, however, then the preliminary information was harmful. This prediction is not as compelling as the one we test here, however, because it involves a change from one trial to the next in the identity of the preliminary information (e.g., previous trial a T, current trial an S). It seems more likely that the outcome of processing a given piece of information would influence later processing of that same information than that processing of a given piece of information would influence later processing of a different piece of information.

be used to gauge and correct for the effects of exact repetition, since exact repetitions should produce just as much effect in the control conditions as in the experimental conditions. The indicator for sequential dependencies in readiness adjustment, then, is the presence a larger exact repetition effect in the experimental condition than the control condition. This indicator is present to a greater degree in the experiments with letters varying in size (18 ms difference in effect sizes) and letters varying in color (17 ms difference) than in the one with visually similar letters (11 ms difference), supporting our earlier conclusion that readiness adjustment took place in the first two cases but not the third. Unfortunately, these results can only be regarded as suggestive, because their statistical reliability is very weak. The relevant condition by previous response interaction was only marginally significant with letters varying in color, $F(1,62) = 3.0981$, MSE = 1424.7, $p < 0.10$, and it did not approach significance with letters varying in size (or, of course, visually similar letters).

In summary, it seems that sequential effects may provide an additional indicator of readiness adjustments, based on short-term fluctuations in the use of preliminary information. Specifically, readiness adjustments are suggested when RTs in the experimental condition, more than the control, show a dependence on whether or not a preceding stimulus with the same preliminary information also had the same response. This pattern suggests readiness adjustment based on the predictive relationship between the preliminary information and the response, because it indicates that sensitivity to peliminary information/response conjunctions is present only when preliminary information is predictive of the response (i.e., in the experimental condition). Technically, this pattern should be verified by a statistical test comparing the effect of the preceding response across the two conditions, and future experiments relying on this indicator should give special consideration to issues of statistical power for this test.

General discussion

We have studied a new paradigm for examining, within the context of a Go versus No-go RT task, the influence of preliminary information obtained before perceptual analysis of a stimulus has finished. The basic idea hinges on the cuing effect demonstrated in experiment 1. Specifically, a cue leads to faster responses when it predicts that the Go response is likely than when it predicts that the Go response is unlikely. This effect increases slightly with the time between cue and imperative stimulus onset, at least up to about 400 ms. Appropriate control conditions indicate that this effect is not an artifact of differences in simple stimulus probability.

In experiments 2–7, preliminary information from easily discriminable features of a single stimulus took on the same logical status as the cues used in experiment 1. The question was whether comparable cuing effects would be produced by preliminary information available early in the perceptual analysis of the imperative stimulus itself.

The results of experiments 2–6 indicate that early information about the shape of an imperative stimulus (i.e., letter name) does produce effects analogous to those of a prior cue. In experiments 2 and 3, subjects responded to letters of one color but not another, and letter name was predictive of the response. Subjects responded more rapidly when letter name predicted the Go response than when it predicted the No-go response, and this effect was larger when the color discrimination was difficult than when it was easy. Experiment 5 showed that an analogous effect of preliminary information about letter name could be obtained when size rather than color was the imperative dimension. Letter name did not produce a Go probability effect in experiment 4, also with size as the imperative dimension, but sequential analyses indicate that the effect was concealed by letter-name-specific practice on the size discrimination, which artifactually increased the probability effect in the control condition.

The results of experiment 7, on the other hand, indicate that preliminary perceptual information about shape does not always produce a Go probability effect comparable to that of a prior cue. When the four stimulus alternatives consist of two pairs of visually similar letters, preliminary shape information could in principle indicate which of the two pairs of letters the imperative stimulus belongs to. This information, however, did not have any effect on Go RT. Previous evidence (Miller 1982a) suggested that no response preparation results from preliminary perceptual information indicating the visually similar letter pair to which a stimulus belongs. The present results thus argue against an explanation of the previous results in which preliminary information leaves the perceptual system but has no consequences beyond the decision level. Instead, it appears that such preliminary information never leaves the perceptual system at all.

With respect to the controversy between discrete and continuous models, a particularly important issue is whether the cuing effects of preliminary letter name information indicate that the perceptual system transmits partial information before it has finished with the analysis of the imperative stimulus. To address this issue, it is important to be sure that the Go probability effect arises at a post-perceptual stage of processing. If the Go probability arises within perceptual processing, then it does not indicate that the perceptual system can transmit preliminary output to later processes.

The results of experiments 3 and 5 clearly indicate that the effect of Go probability is post-perceptual. Both show that the effect is not specific to an imperative attribute that is predicted by the preliminary information, but instead transfers to other stimuli sharing the same response. This is evidence against a perceptual effect, because such an effect should be specific to the particular perceptual feature predicted by the preliminary information. The results of experiment 6 provide a further clue as to the locus of the Go probability effect by suggesting that it must occur before response activation. The crucial finding is that the Go probability effect does not transfer to Go responses elicited by a stimulus on another modality. In combination, then, the results of experiments 3, 5, and 6 suggest that Go probability has its effect at a decision stage intervening between perceptual analysis and motor activation.

With respect to the question of when the perceptual system transmits output, the results of the present studies agree well with the predictions of the ADC model (Miller 1982a, 1983, 1988). As in previous studies, it appears that preliminary information is transmitted by the perceptual system if and only if it constitutes a distinct, discretely codable stimulus attribute (cf., Miller 1982a, 1983). In particular, it appears that preliminary information about letter name can be transmitted to the decision process, where it influences response readiness, but preliminary evidence about membership in a visually similar pair cannot be transmitted. The former finding converges with previous evidence that other distinct and highly codable types of preliminary information can support response preparation (e.g., Coles and Gratton 1986; Coles et al. 1985; Eriksen and Schultz 1979; Miller 1982a, 1983, 1987a; Miller and Hackley 1989). Like earlier demonstrations, the present results emphasize the idea that preliminary output can sometimes be transmitted even when only a single physical stimulus is presented.

The present results extend the earlier demonstrations of preliminary output in three ways. First, they show that preliminary information can have effects even in tasks with very simple response-choice requirements. Although some previous effects attributed to preliminary information have been argued to arise in response selection processes (e.g., Reeve and Proctor 1984), the relative simplicity of that process in a Go versus No-go task makes such an explanation highly unlikely for the present effects.

Second, they show that the perceptual system transmits preliminary output regarding stimulus attributes that are task-irrelevant. Previous studies have shown that preliminary output is transmitted concerning relevant attributes of both relevant and irrelevant stimuli. In the present experiments, however, subjects were told to attend to a relevant stimulus attribute which completely determined the correct response, yet the results suggested that preliminary information about another attribute had an effect on the decision process. Thus, this finding extends the range of conditions under which preliminary perceptual output has been shown to occur.

Third, they seem to show effects of preliminary output on decision-making rather than response preparation. Although effects of preliminary output on response preparation logically imply that preliminary output must have gone through a decision stage (at least with arbitrary S–R mappings), it is useful to be able to observe directly the effect of preliminary output on decision processes. This is particularly useful in the case of stimuli for which no evidence of response preparation was previously found, like the visually similar letters of experiment 7. The present results suggest that preliminary information about these stimuli fails to reach the decision process as well as the response preparation process, supporting the claim that this preliminary information never leaves the perceptual process.

The results of experiment 4 make it clear that the simplest of the paradigms presented here must be used with great care in checking for preliminary output of other types of perceptual information. Even if preliminary output occurs, it may be difficult to demonstrate because of the possibility of complex probability and practice effects. It seems clear that the more elaborate eight-stimulus paradigm of experiments 3 and 5 is a surer test for preliminary output, since it equates both stimulus probability and discrimination practice. On the other hand, it may not always be practical to construct quadruples of similar stimuli (e.g., visually similar letters), and so ancillary indicators based on sequential effects may be useful.

In conclusion, a comparatively clear overall picture is emerging from the results of a number of converging paradigms designed to look for effects of preliminary perceptual information. It appears that preliminary information is transmitted by the perceptual system to later processes, but only when that information fulfills certain criteria. Further research is needed to specify more exactly what types of information satisfy these criteria, but the evidence so far is quite compatible with the ADC model. A reasonable working hypothesis, then, is that the perceptual system transmits preliminary information only after it has activated a discrete internal code for one stimulus attribute.

The overall evidence for the ADC model has come from tasks with an impressive range of complexity. In addition to the present evidence from a Go versus No-go task, there is previous evidence from four-choice RT tasks (Miller 1982a, 1983), four-choice divided attention tasks (Miller 1987a), and two-choice tasks using psychophysiological measures of response preparation (Miller and Hackley 1990; Osman et al. 1988).

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