Perception & Psychophysics
2006, 68 (6), 933-945

Time perception and word recognition: An elaboration of the time-criterion account

TAMSEN E. TAYLOR and STEPHEN J. LUPKER
University of Western Ontario, London, Ontario, Canada

Past research suggests that a time criterion guides responding in speeded word recognition tasks. The time-criterion account has been challenged, however, because it incorrectly predicts equivalent latencies for stimuli of differing difficulty when those stimuli are presented in the same trial block. By requiring participants to perform a lexical decision or naming task but to respond only once they had estimated that 1 sec had elapsed, we investigated the idea that stimulus difficulty effects in response latency might be at least partially due to time perception processes. Consistent with this idea, the participants produced shorter estimates of 1-sec intervals when processing easier stimuli (i.e., time seemed to pass faster when easier stimuli were processed). The implication is that understanding speeded word recognition performance will require looking beyond processes involved in acquiring information about the presented stimulus and examining more general response processes.

A core assumption for researchers who use speeded response tasks is that the response time to any given stimulus is a direct reflection of the time it takes to carry out the relevant processing operations for that stimulus (i.e., to reach a processing goal). With respect to the naming task in particular, in which participants are presented letter strings visually and asked to read them aloud as quickly and as accurately as possible, the assumption is that differences in response times for different stimulus types are direct reflections of the different amounts of time it takes to generate an acceptable phonological code for each of those different stimulus types (e.g., Baluch & Besner, 1991; Colombo & Tabossi, 1992; Kello & Plaut, 2000; Monsell, Patterson, Graham, Hughes, & Milroy, 1992; Tabossi & Laghi, 1992). In general, the idea is that responding in these tasks is controlled by what we can refer to as an *information criterion*. That is, a response will be made when a specified amount of information about the stimulus has been accumulated.

Recently, however, Lupker, Brown, and Colombo (1997) provided evidence that readers' naming responses are also controlled by timing operations—in particular, by the use of a time-based criterion for responding. Specifically, Lupker et al. (1997) argued that readers have an idea when they should be responding on each trial (their criterion placement) and they attempt to initiate their naming responses after that amount of time has elapsed. If this argument is correct, naming latencies clearly reflect more than simply the amount of time required to produce "acceptable" phonological codes from the presented letter strings.

More recently, Rastle, Kinoshita, Lupker, and Coltheart (2003) and Lupker, Kinoshita, Coltheart, and Taylor (2003) provided evidence that similar operations are at work in other speeded tasks, including lexical decision tasks, picture-naming tasks, and sum calculation tasks. If these arguments are correct, understanding performance in these experimental tasks (and in fact, understanding the nature of reading itself) will necessitate an understanding of the general processes, including criterion setting, involved in making speeded responses.

Although there is reasonable evidence supporting Lupker et al.'s (1997) time-criterion account, multiple questions remain. One of the main criticisms of the time-criterion account (e.g., Kello & Plaut, 2000) has been that if responding were essentially controlled by a time criterion, it is not clear why there would ever be a main effect of stimulus difficulty on response latency when the experimental stimuli consist of easy and difficult stimuli presented in a random order. This is a reasonable criticism because a key assumption of Lupker and colleagues (e.g., Lupker et al., 1997; Taylor & Lupker, 2001a) has been that participants maintain only one time criterion within a set of trials, at least when the stimuli are of a similar nature (e.g., words and nonwords; see Lupker et al., 2003). As a result, main effects of stimulus difficulty on response latency should essentially disappear when stimuli are presented in a single set of trials, because all the items should be responded to at essentially the same point in time.

In an attempt to explain stimulus difficulty effects on response latency that occur within a set of randomly mixed difficult and easy items, Lupker et al. (1997) suggested

This research was based on a dissertation presented by the first author in partial fulfillment of the requirements for a Ph.D. at the University of Western Ontario. This work was partially supported by Natural Sciences and Engineering Research Council of Canada Grant A6333 to the second author. The experiments presented herein were also presented in poster format at the 45th Annual Meeting of the Psychonomic Society, Minneapolis. We thank Sachiko Kinoshita, Claudette Fortin, Chris Kello, and two anonymous reviewers for their comments on earlier drafts of the manuscript. Correspondence concerning this article may be addressed to either T. E. Taylor or S. J. Lupker, Department of Psychology, University of Western Ontario, London, ON, N6A 5C2 Canada (e-mail: tamsentaylor@hotmail.com or lupker@uwo.ca).

that participants may use the time criterion in a somewhat flexible fashion. In sets of trials where stimulus types of differing difficulties are randomly mixed, the participants may have to delay responding even after the time criterion has been reached when the stimulus is too difficult. Similarly, participants may not always be willing to wait until the time criterion is reached whenever the stimulus is very easy. Thus, the participants may initiate their response early. Due to this flexibility in how the time criterion is used, one would expect that a stimulus type that was easy to process (e.g., high-frequency words) would, on average, be responded to more rapidly than a stimulus type that was more difficult to process (e.g., nonwords). We will refer to this idea as the *flexible time-criterion* hypothesis.

An alternative attempt to reconcile the time-criterion account with stimulus difficulty effects was offered by Taylor and Lupker (2001a, 2001b). If participants truly are using a time criterion to guide responding, they must be monitoring the passage of time while they are simultaneously processing the stimulus. In such a circumstance, any experimental factors that affect the perception of time would be expected to affect performance. For example, any factor that makes time appear to pass more slowly should increase the point in actual time at which the participants think that the time criterion has been reached. The expected result would be a lengthening of response latencies. Thus, it is theoretically possible that differences in time perception could provide at least part of the explanation for why main effects of stimulus difficulty on response latency continue to appear within a set of trials. We will refer to this hypothesis as the *time perception* hypothesis.

The goal of the present research was to determine whether time perception actually does influence responding in speeded word recognition tasks and to evaluate to what extent the effect of stimulus difficulty on response latency in randomly mixed sets of stimuli could be due to effects of time perception, rather than to effects of a flexible time criterion or effects of an information criterion. We will begin by presenting a brief review of important and relevant findings in the time perception literature.

Effects of Stimulus Difficulty on Time Perception

When participants are asked to simultaneously monitor the passage of time and perform another task,[1] many researchers have reported that the difficulty of the concurrent nontemporal task influences time perception. Typically, the perceived duration of a presented interval is inversely related to the difficulty of the concurrent nontemporal task (e.g., Brown, 1985; Brown, Stubbs, & West, 1992; Casini & Macar, 1997; Chastain & Ferraro, 1997; Hicks, Miller, & Kinsbourne, 1976; Hochhaus, Swanson, & Carter, 1991; McClain, 1983; Thomas & Weaver, 1975; Warm & McCray, 1969). The articles most relevant to the present discussion about stimulus difficulty effects in word recognition are those by Warm and McCray, Hochhaus et al., and Chastain and Ferraro, because those researchers used words as stimuli.

Warm and McCray's (1969) words varied in frequency and length. Longer and less frequent words are, of course, more difficult to process (i.e., to respond to in speeded response tasks) than are their shorter and/or more frequent counterparts. All the stimuli were presented for exactly 1 sec, and the participants were asked to estimate how long the stimuli were presented by marking the appropriate duration on a vertical scale ranging from 0.09 to 9.99 sec (with increments of 0.01 sec). There were significant effects of word frequency and word length, with participants reporting longer exposure durations for the shorter and more frequent stimuli (i.e., time appeared to pass more rapidly when the participants were monitoring the duration of shorter and more frequent stimuli). Hochhaus et al. (1991) replicated Warm and McCray's findings, using a range of exposure durations (17–1,075 msec) in a number of experiments, showing that this effect is reasonably robust.

Similar results were reported by Chastain and Ferraro (1997), using a slightly different task. Participants were trained to categorize durations of 83 msec as "1" and durations of 167 msec as "4." The participants were told that stimulus presentation times would fall within this range and that they were to categorize the experimental stimuli as having been presented for a duration corresponding to "1," "2," "3," or "4." All the stimuli were actually presented for the two durations used during training—that is, either 83 or 167 msec. The stimuli were high- versus low-frequency words and ambiguous versus unambiguous words. In all the reported experiments, Chastain and Ferraro replicated the finding that the stimuli that are easier to process (the high-frequency words and the ambiguous words, respectively) were judged to be presented for more time than their more difficult counterparts, even though the presentation durations were identical across conditions. Thus, a variety of researchers have reported the result that participants perceive that more time has passed when an easy word is presented than when a more difficult word is presented, even when the presentation time is objectively the same in both conditions.

How might this effect manifest itself in a speeded word recognition task if responding were being controlled by a time criterion, and how might that process lead to stimulus difficulty effects in sets of randomly mixed items? Because participants tend to perceive easy-to-process stimuli as being presented for a longer time than difficult-to-process stimuli when they are actually presented for the same duration, the implication is that some internal timing process accumulates some measure of time more quickly when easier stimuli are being processed. This means that although participants may be responding at exactly the same point in *subjective* time for all the stimuli (at the point at which the time criterion is set), in *objective* time (as measured by response times) the amount of time passing before the time criterion is reached will be less when they are processing the easy stimuli than when they are processing the difficult stimuli. Thus, even if the time criterion were in exactly the same position for all the stimuli and absolutely controlled responding, the participants would still be expected to produce shorter latencies when responding to the easy stimuli than when responding to the difficult stimuli. As such, at least part of the reason why noticeable latency differences exist between easy and difficult stimuli when they are presented in randomly mixed sets can be explained within the time-criterion framework, without assuming that the criterion is flexible and often violated. The present research was an attempt to investigate this possibility.

The Present Research

Recall that, according to an information criterion account, the explanation for the effects of stimulus difficulty on response latency is that the amount of information required in order to respond (i.e., in order to reach the level required by the information criterion) will take longer to accumulate for a difficult item. In contrast, within the time-criterion account, these effects may be the result of either a flexible criterion (participants may start their response early for very easy items, and delay responding for very difficult items) or differences in time perception, as was outlined in the previous section.

One way to test between these three explanations of stimulus type effects is to require participants to use a time criterion that is situated at a point after which processing is typically completed for a task. This was accomplished in the present circumstances by asking participants to respond only after they believed that a specified time period (i.e., 1 sec) had passed. We will refer to this as an *internal-timing* manipulation. If participants use only an information criterion to guide responding, effects of stimulus difficulty should no longer be observed under an internal-timing manipulation, because the participants would have delayed their response past the point at which processing was completed and, therefore, enough information should have been acquired to produce responses for all the items.

This internal-timing manipulation should also cause stimulus type latency differences to disappear if the explanation for those differences is that the time criterion is flexible (the flexible criterion hypothesis). That is, the participants would have no reason to respond (indeed, they should be trying *not* to respond) before reaching the imposed criterion, so the flexibility in the use of the time criterion that allows participants to respond before reaching the criterion would not be operating. In addition, the participants should not have to delay their response due to the processing of a difficult item not being completed on time, because the criterion should be reached after processing has been completed. Therefore, the flexibility in the use of the time criterion that allows participants to delay responding because they have not acquired enough information should also not be operating. Thus, both the information criterion account and the flexible time-criterion hypothesis would predict that stimulus difficulty differences should be eliminated if participants are required to respond at a point later than they would respond under (typical) speeded instructions.

On the other hand, if the time perception hypothesis is correct and differences in reaction time caused by stimulus difficulty are actually, at least in part, due to time perception processes, the predictions are somewhat different. These time perception processes should continue to operate during the trial, regardless of where any internal time criterion is positioned. The result would be that stimulus difficulty effects would remain in any internal-timing condition, even when the criterion was positioned after the point at which processing would be completed.

If effects of stimulus difficulty were observed in an internal-timing situation, it might be possible to rescue an information criterion account or the flexible time-criterion hypothesis if one could attribute those effects to late-level response processes. For example, in delayed-naming tasks in which participants are given an external cue to respond, frequency effects are sometimes, although not always, found (e.g., the effect was reported by Balota & Chumbley, 1985, and Goldinger, Azuma, Abramson, & Jain, 1997, but not by Forster & Chambers, 1973, or McRae, Jared, & Seidenberg, 1990). Effects of word frequency in delayed naming are presumed to be due to articulatory differences, rather than to differences in gathering information about the phonological code of the item, and these types of effects certainly could appear in our internal-timing condition. If any effects in the internal-timing condition were due to late-level response processes, however, similar effects should be observed when a delayed response is triggered by an external cue. For example, if it takes longer to begin articulation of a nonword than a word even after phonological coding is complete, that difference should emerge regardless of whether the response cue was generated internally or externally.

According to the information criterion account and the flexible time-criterion hypothesis, therefore, any stimulus difficulty effects that remain in the internal-timing condition should also be observed in an external cue condition. In contrast, the time perception hypothesis predicts stimulus difficulty effects in the internal-timing condition similar to those that occur under typical speeded instructions but predicts that these effects should be expected to be much smaller when an external cue is used (since timing operations would no longer differentially affect responding). To examine this issue, our experiments also involved delayed external cues (what we refer to as the *external cue* condition).

It should be noted that prior investigations in which word stimuli were used (i.e., Chastain & Ferraro, 1997; Hochhaus et al., 1991; Warm & McCray, 1969) involved a duration estimation task (i.e., the stimuli were presented for a set period of time, and the participants had to estimate the length of that presentation time). Although this is a standard methodology, it is not the best way to investigate the potential link between stimulus difficulty and time perception in speeded tasks. Most crucially, there is no control over what the participants are actually doing during the interval in any of these experiments. The conclusion that processing difficulty affects time estimates is based on the assumption that the participants actually are carrying out essentially the same processing operations on the various types of stimuli and that there is a processing difficulty difference between them. When participants are not required to process the stimulus in any particular way, as was the case in these experiments, there is no guarantee that this assumption is valid. The version of the timing task used in the present experiments does require the participants to process all the stimuli in a similar way, as well as allowing the experimenter to monitor the accuracy of that processing. In addition, this task more closely parallels how the timing process would actually impact any speeded response task (because they are production, rather than estimation, tasks), allowing for a much better comparison with results in a typical speeded response situation.

EXPERIMENT 1

Experiment 1 was a lexical decision experiment with three different instruction conditions (a between-subjects manipulation). In the speeded condition, the instructions about speed and accuracy were the ones typically given to participants in this task: "Please respond as quickly and as accurately as possible." In the external cue condition, the participants were presented with an external cue (a row of number signs above the letter string) 1 sec after the onset of the letter string and were instructed to make their lexical decision response as accurately as possible and as soon as the external cue appeared, but not before. In the internal-timing condition, the participants were also instructed to make their lexical decision response as accurately as possible and to respond when they thought that the item had been on the screen for exactly 1 sec.

The easy stimuli (i.e., in the sense that they should have relatively short latencies, in comparison with nonwords [the difficult stimuli] in a speeded lexical decision task) were high-, medium-, and low-frequency regular words, and the difficult stimuli were pronounceable nonwords (these stimuli were subsets of the items used in naming experiments reported in Taylor & Lupker, 2001a, and were used in all the experiments presented here). In the speeded condition, the expectation was that high-frequency words should be responded to the most quickly, that responses to the medium-frequency words should be the second fastest, that the next fastest responses should be to the low-frequency words, and that the slowest responses should be to the nonwords. This speeded condition would provide important confirmatory evidence that our characterization of the difficulty of the stimuli was appropriate and that processing was typically completed in under 1 sec, as well as providing the baseline for the comparison with the external cue and internal-timing conditions. The crucial question was whether the same stimulus type differences that occurred in the speeded condition would also emerge in the internal-timing and/or external cue conditions.

Method

Participants. Ninety undergraduate students received course credit in an undergraduate introductory psychology course for their participation in Experiment 1 (30 in each instruction condition). The participants reported having normal or corrected-to-normal vision and being native speakers of English.

Apparatus. The stimuli were presented on an IBM clone computer system (Trillium Computer Resources Model 316S-80MS); the monitor was a TTX Multiscan Monitor (Model 3435P), and a button box was used to record the responses.

Stimuli. The word stimuli (the easy stimuli) consisted of three groups of 12 regular words, a high-frequency group (mean frequency = 462.0, frequency range = 142–897), a medium-frequency group (mean frequency = 46.8, frequency range = 15–72), and a low-frequency group (mean frequency = 4.4, frequency range = 1–14). Frequencies were taken from Kučera and Francis (1967). A group of 36 nonwords were also selected (the difficult stimuli). All of the stimuli are listed in the Appendix. The participants received eight practice trials at the beginning of each experiment, and these practice stimuli are also listed in the Appendix.

Procedure. The participants were tested individually. The participants were told that they would see strings of letters and that they were to press the button marked WORD if they thought the letter string spelled a real English word and they were to press the button marked NONWORD if they thought the letter string did not spell a real English word. The participants were asked whether they were right- or left-handed. Half of the participants used their dominant hand for word responses, and the other half of the participants used their nondominant hand for word responses.

The participants in the speeded condition were given the standard instructions to respond as quickly and as accurately as possible. The participants in the external cue condition were instructed to respond as accurately as possible but to delay their response until the row of number signs (the external cue) appeared above the letter string and to respond as quickly as possible after the number signs appeared. The participants in the internal-timing condition were instructed to respond as accurately as possible, and to respond when they thought that the letter string had been present on the computer screen for exactly 1 sec.

In all the conditions, a fixation cross appeared in the middle of the screen and remained until all the trials were complete. The stimuli were presented centered above the fixation point and remained until the button box registered a response. There was a 2-sec interval between the participant's response and an auditory cue indicating that the next trial was about to begin. The stimulus was presented 1 sec after the cue (for a total intertrial interval of 3,000 msec). In the external cue condition, a row of number signs was presented above the letter string 1 sec after stimulus onset. The participants were given 8 practice trials (all the participants received the practice trials in the same order). The 72 experimental trials followed in a random order (different for each participant).

In the internal-timing condition, feedback was provided for the timing aspect of the trials. In an attempt to constrain responses to a reasonable approximation of 1 sec, a high-pitched warning tone sounded when the responses were shorter than 500 msec, and a lower pitched warning tone sounded when the responses were longer than 1,500 msec. To accustom the participants in the internal-timing condition to these tones and their meaning, prior to the practice trials, the high-pitched tone was played for these participants five times, and then the lower pitched tone was played five times. The participants were instructed to use the tones as feedback and to adjust their response times appropriately. After the feedback instructions, as in the other two conditions, the 8 practice trials were presented to the participants, and the 72 experimental trials followed.

Results

Data trimming. Trials on which the lexical decision response was incorrect were eliminated from the latency analyses (with speeded instructions, 1.4% of the high-frequency word trials, 5.0% of the medium-frequency word trials, 11.7% of the low-frequency word trials, and 3.6% of the nonword trials; with internal-timing instructions, 0% of the high-frequency word trials, 1.9% of the medium-frequency word trials, 6.4% of the low-frequency word trials, and 8.4% of the nonword trials; with external cue instructions, 0.3% of the high-frequency word trials, 1.1% of the medium-frequency word trials, 5.0% of the low-frequency word trials, and 3.9% of the nonword trials). In the speeded instruction condition, a trial was considered an outlier if the response time was less than 150 msec or greater than 1,500 msec (no trials were below the 150-msec cutoff; an additional 1.7% of the high-frequency word trials, 3.3% of the medium-frequency word trials, 3.0% of the low-frequency word trials, and 8.5% of the nonword trials were above the 1,500-msec cutoff). In the internal-timing condition, a trial was considered an outlier if the response time was less than 500 msec or greater than 1,500 msec (on 3.8% of the high-frequency word trials, 3.3% of the medium-frequency word trials, 0.8% of the low-frequency word trials, and 0.2% of the nonword trials, the responses were too fast; on 3.1% of the high-frequency word trials, 3.3% of the medium-frequency word trials, 2.8% of the low-frequency word trials, and 5.8% of the nonword trials, the responses were too slow). In the external cue condition, a trial was considered an outlier if the response occurred less than 50 msec after the cue presentation or more than 1,000 msec after the cue presentation (on 2.8% of the high-frequency word trials, 1.7% of the medium-frequency word trials, 1.9% of the low-frequency word trials, and 1.6% of the nonword trials, the responses were too fast; on 2.8% of the high-frequency word trials, 2.2% of the medium-frequency word trials, 3.9% of the low-frequency word trials, and 7.2% of the nonword trials, the responses were too slow). Outliers were changed to the cutoff value and included in the reaction time analyses. Note that trials that were both outliers and lexical decision errors were classified as lexical decision errors only and were eliminated from the reaction time analyses.

Overall comparisons. The subject means and error rates for all three conditions are presented in Table 1. A 4 (stimulus difficulty) × 3 (instruction type) ANOVA was performed to compare the influence of instruction type on the stimulus difficulty effects. There was a significant interaction [by subjects, $F_1(6,261) = 6.34$, $p < .001$; by items, $F_2(6,136) = 7.17$, $p < .001$], and both main effects were also significant [stimulus difficulty, $F_1(3,261) = 86.75$, $p < .001$, and $F_2(3,68) = 28.56$, $p < .001$; instruction type, $F_1(2,87) = 107.32$, $p < .001$, and $F_2(2,136) = 2,925.32$, $p < .001$].

Table 1
Mean Latencies (RTs, in Milliseconds) and Error Rates (ERs, in Percentages) for Experiment 1 As a Function of Stimulus Difficulty

	Speeded		Internal Timing		External Cue	
Stimulus Type	RT	ER	RT	ER	RT	ER
Regular words						
High frequency	685	1.4	798	0.0	1,361	0.2
Medium frequency	712	5.0	826	1.9	1,372	1.1
Low frequency	774	11.7	898	6.4	1,371	5.0
All words	722	6.0	839	2.8	1,368	2.1
Nonwords	859	3.6	975	8.4	1,434	3.9

Analysis of individual instruction conditions. An analysis of responses was performed for each instruction condition on the basis of the frequency grouping (high, medium, or low) of the words plus the nonwords. In general, the pattern was as expected, with the high-frequency words responded to more quickly than the medium-frequency words, the medium-frequency words responded to more quickly than the low-frequency words, and the low-frequency words responded to more quickly than the nonwords. In the speeded condition, the difference between high-frequency and medium-frequency words was significant by subjects [$t_1(29) = 2.01$, $p < .05$], but not by items; the difference between medium-frequency and low-frequency words was significant by subjects and marginally significant by items [$t_1(29) = 4.42$, $p < .001$; $t_2(22) = 1.59$, $p < .10$]; and the difference between low-frequency words and nonwords was significant by both subjects and items [$t_1(29) = 4.63$, $p < .001$; $t_2(46) = 2.22$, $p < .05$; all tests one-tailed]. Similarly, in the internal-timing condition, the differences were all significant (using one-tailed tests) [high-frequency and medium-frequency words, $t_1(29) = 2.48$, $p < .01$, and $t_2(22) = 1.32$, $p < .10$; medium-frequency and low-frequency words, $t_1(29) = 5.26$, $p < .001$, and $t_2(22) = 2.81$, $p < .01$; low-frequency words and nonwords, $t_1(29) = 4.00$, $p < .05$, and $t_2(46) = 3.29$, $p < .01$]. However, in the external cue condition, only the difference between the nonwords and the low-frequency words was significant [$t_1(29) = 4.47$, $p < .001$; $t_2(46) = 5.62$, $p < .001$; all tests one-tailed].

Next, for each instruction condition, a correlation was performed to determine the relationship between lexical decision latency and the natural logarithm of word frequency. There was a significant negative correlation between these two variables in the speeded condition ($r = -.45$, $p < .01$, one-tailed) and also in the internal-timing condition ($r = -.65$, $p < .001$, one-tailed). However, although there was a negative correlation between these two variables in the external cue condition, it was not statistically significant ($r = -.18$, n.s.).

Comparisons between speeded and internal-timing conditions. The analyses above suggest that the speeded and the internal-timing instructions produced very similar patterns in response latency as a function of stimulus difficulty. To investigate this issue further, a 4 (stimulus difficulty) × 2 (instruction type) ANOVA was performed on the subject and item means in each condition. As was expected, there were significant main effects of stimulus difficulty [$F_1(3,174) = 79.75$, $p < .001$; $F_2(3,68) = 24.79$, $p < .001$] and instruction type [$F_1(1,58) = 6.18$, $p < .05$; $F_2(1,184) = 184.44$, $p < .001$]. More important, the interaction between stimulus difficulty and instruction type was virtually nonexistent [$F_1(3,174) = 0.09$, n.s.; $F_2(3,68) = 0.19$, n.s.].

Comparisons between external cue and internal-timing conditions. The analysis above also suggests that the effects of stimulus difficulty on response latency were noticeably different under external cue and internal-timing instructions. To investigate this further, a 4 (stimulus difficulty) × 2 (instruction type) ANOVA was performed on the subject and item means in each condition. There were significant main effects of stimulus difficulty [$F_1(3,174) = 49.94$, $p < .001$; $F_2(3,68) = 37.74$, $p < .001$] and instruction type [$F_1(1,58) = 125.59$, $p < .001$; $F_2(1,68) = 4{,}302.51$, $p < .001$]. Most important, there was a significant interaction between stimulus difficulty and instruction type [$F_1(3,174) = 11.19$, $p < .001$; $F_2(3,68) = 14.09$, $p < .001$], due to the fact that there were no latency differences between the word conditions under the external cue instructions.

Discussion

In the speeded condition, in which the participants were given the standard instructions to respond as quickly and as accurately as possible, the ordinal relationships between the means of the four conditions followed the pattern predicted by the relative frequency of the items. Thus, the assumptions made about the relative processing difficulty of these stimuli were validated. As well, an inspection of the mean response times shows that responses to the stimuli used here are typically made in under 1 sec, an important point because we are arguing that processing should essentially be complete by that time (i.e., when participants are asked to respond after the item has been on the computer screen for 1 sec, any processing required for an accurate response should have been completed).

The internal-timing condition in Experiment 1 showed that the production of time intervals is influenced by the difficulty of a concurrently performed lexical decision, with intervals produced while more difficult stimuli are processed being longer than intervals produced while easier stimuli are processed. This result supports the time perception hypothesis by showing that differences in time perception, along with the use of a time criterion, could be an important source of differences in response latencies to different stimulus types.

Equally importantly, there was a nonsignificant interaction between stimulus difficulty and instruction type when the speeded and the internal-timing conditions were compared, but a significant interaction between these same variables when the external cue and internal-timing conditions were compared. This finding indicates that overall, different processes are operating under external cue instructions than under the other two instruction types but that similar processes appear to be operating under speeded and internal-timing instructions. This result provides further support for the idea that time perception processes, working in conjunction with the use of a time criterion, may provide a reasonable explanation of the effects of stimulus difficulty on response latencies in speeded word recognition tasks.

An examination of the external cue condition showed that there was still a significant effect of stimulus difficulty on response latency. In particular, although there were no differences among the three word types, nonword latencies were longer than word latencies. Because half of the participants made the *word* responses with their dominant hand and half with their nondominant hand, this difference cannot simply be an effect of differential responding with the dominant hand. It is quite possible that this effect remained in the external cue condition because of the influence of stimulus difficulty on processes occurring after response initiation. For example, as Balota and Abrams (1995) have shown, stimulus difficulty can affect the acceleration and force of the response movement. Thus, it is possible that the response triggered by a nonword was actually a slower movement than the response triggered by a word; this would result in the button's being pressed more quickly after a word than after a nonword in all the conditions. In any case, the important finding here is that the size of the effect of stimulus difficulty on response latency was significantly smaller in the external cue condition than in the internal-timing (and speeded) condition. The statistically significant interaction found between the internal-timing condition and the external cue condition indicates that different processes are operating in the two conditions.

EXPERIMENT 2

As has been noted, the experiments reported by Lupker and colleagues (e.g., Lupker et al., 1997) mainly involved the naming task. Thus, in order to round out the argument that the effects of stimulus difficulty on time perception are a major source of response latency differences, it is necessary to show that the effects found in Experiment 1 in a lexical decision task will also be found in a naming task. This was the issue investigated in Experiment 2, using the same stimuli as those in Experiment 1. Experiment 2 paralleled the lexical decision experiments presented here, with naming performed under speeded, external cue, and internal-timing conditions. Again, the key question was whether these same stimulus type differences found in the speeded condition would emerge in the internal-timing and/or external cue conditions.

Method

Participants. One hundred twenty (40 in each instruction condition) undergraduate students received course credit in an undergraduate introductory psychology course for their participation in Experiment 2. The participants reported having normal or corrected-to-normal vision and being native speakers of English. None of the participants had taken part in Experiment 1.

Apparatus, Stimuli, and Procedure. The apparatus, stimuli, and procedure were the same as those in Experiment 1, except that, because the participants were instructed to read the items aloud, a microphone was used instead of the button box to record timing (naming) latencies and the experimenter was present during the experiment to record errors.

Results

Data trimming. Trials on which the naming response was incorrect (the participants named the word incorrectly or stuttered or the response was incomplete) were eliminated from the latency analyses (with speeded instructions, 0.4% of the high-frequency word trials, 0.2% of the medium-frequency word trials, 0.4% of the low-frequency word trials, and 4.4% of the nonword trials; with internal-timing instructions, 0.2% of the high-frequency word trials, 0.4% of the medium-frequency word trials, 0.4% of the low-frequency word trials, and 5.9% of the nonword trials; with external cue instructions, 0.0% of the high-frequency word trials, 0.6% of the medium-frequency word trials, 1.0% of the low-frequency word trials, and 3.8% of the nonword trials). Trials on which the microphone did not pick up the beginning of the participants' utterance were considered mechanical errors, and these accounted for an additional 2.2% of the trials in the speeded condition, 2.6% of the trials in the internal-timing condition, and 5.9% of the trials in the external cue condition. In the speeded condition, a trial was considered an outlier if the response time was less than 150 msec or greater than 1,500 msec (on no trials were the responses too fast; on 0.0% of the high-frequency word trials, 0.2% of the medium-frequency word trials, 0.0% of the low-frequency word trials, and 0.8% of the nonword trials, the responses were too slow). In the internal-timing condition, a trial was considered an outlier if the response time was less than 500 msec or greater than 1,500 msec (on 5.8% of the high-frequency word trials, 4.2% of the medium-frequency word trials, 2.7% of the low-frequency word trials, and 2.9% of the nonword trials, the responses were too fast; on 0.0% of the high-frequency word trials, 0.2% of the medium-frequency word trials, 0.2% of the low-frequency word trials, and 0.6% of the nonword trials, the responses were too slow). In the external cue condition, a trial was considered an outlier if the response time occurred less than 50 msec after the cue presentation or more than 1,000 msec after the cue presentation (on 0.0% of the high-frequency word trials, 0.4% of the medium-frequency word trials, 0.2% of the low-frequency word trials, and 0.6% of the nonword trials, the responses were too fast; on no word trials and 0.4% of the nonword trials, the responses were too slow). Outliers were changed to the cutoff value and included in the reaction time analyses. Note that in all the conditions, trials that were both outliers and naming errors were classified as naming errors only and were eliminated from the reaction time analyses.

Overall comparisons. The subject means and error rates are presented in Table 2. A 4 (stimulus difficulty) $\times$ 3 (instruction type) ANOVA was performed to compare the influence of instruction type on the stimulus difficulty effects. There was a significant interaction [$F_1(6,351) = 15.74$, $p < .001$; $F_2(6,136) = 12.90$, $p < .001$], and both main effects were also significant [stimulus difficulty, $F_1(3,351) = 67.71$, $p < .001$, and $F_2(3,68) = 16.24$, $p < .001$; instruction type, $F_1(2,117) = 460.51$, $p < .001$, and $F_2(2,136) = 9{,}114.94$, $p < .001$].

Analysis of individual instruction conditions. As in Experiment 1, an analysis of responses was performed for each instruction condition on the basis of the frequency grouping (high, medium, or low) of the words plus the nonwords. In the speeded condition, the difference between the high- and the medium-frequency words was marginally significant in the subject analysis [$t_1(39) = 1.64$, $p < .10$] whereas the other differences were all significant (using one-tailed tests) [medium-frequency and low-frequency words, $t_1(39) = 3.24$, $p < .01$; low-frequency words and nonwords, $t_1(39) = 8.76$, $p < .001$, and $t_2(46) = 4.09$, $p < .001$]. Similarly, in the internal-timing condition, these differences were all significant, except for the difference between the high- and the medium-frequency words (using one-tailed tests) [medium-frequency and low-frequency words, $t_1(39) = 3.40$, $p < .01$, and $t_2(22) = 1.95$, $p < .05$; low-frequency words and nonwords, $t_1(39) = 4.18$, $p < .001$, and $t_2(46) = 2.39$, $p < .05$]. However, in the external cue condition, there were no statistically significant effects of stimulus difficulty.

Table 2
Mean Latencies (RTs, in Milliseconds) and Error Rates (ERs, in Percentages) for Experiment 2 As a Function of Stimulus Difficulty

	Speeded		Internal Timing		External Cue	
Stimulus Type	RT	ER	RT	ER	RT	ER
Regular words						
High frequency	610	0.4	726	0.2	1,347	0.0
Medium frequency	619	0.2	726	0.4	1,351	0.6
Low frequency	640	0.4	753	0.4	1,350	1.0
All words	623	0.3	735	0.3	1,350	0.6
Nonwords	720	4.4	789	5.9	1,358	3.8

Next, for all the instruction conditions, a correlation was performed to determine the relationship between naming latency and the natural logarithm of word frequency for the word stimuli. There was a significant negative correlation between these two variables in the speeded instruction condition ($r = -.32$, $p < .05$, one-tailed) and in the internal-timing condition ($r = -.34$, $p < .05$, one-tailed), but not in the external cue condition ($r = -.07$, n.s.).

Comparisons between speeded and internal-timing instructions. The analyses above suggest that the speeded and the internal-timing conditions showed very similar patterns in naming latency as a function of stimulus difficulty. To investigate this issue further, a 4 (stimulus difficulty) $\times$ 2 (instruction type) ANOVA was performed on the subject and item means in each condition. As was expected, there were significant main effects of stimulus difficulty [$F_1(3,234) = 75.83$, $p < .001$; $F_2(3,68) = 17.15$, $p < .001$] and instruction type [$F_1(1,78) = 15.29$, $p < .001$; $F_2(1,68) = 507.38$, $p < .001$]. There was also a significant interaction between stimulus difficulty and instruction type [$F_1(3,234) = 5.68$, $p < .01$; $F_2(3,68) = 8.42$, $p < .001$].

To analyze the interaction further, independent sample t tests were performed on the sizes of the effects of stimulus difficulty on naming latency for the two instruction conditions (speeded and internal timing). The only significant difference was the effect of instruction type on the difference between low-frequency words and nonwords

[$t_1(78) = 3.49$, $p < .001$; $t_2(46) = 3.43$, $p < .001$]. The other effects of instruction type on the size of the effect of stimulus difficulty were not statistically significant.

Comparisons between external cue and internal-timing conditions. The analyses above suggest that the effects of stimulus difficulty on naming latency were different under external cue and internal-timing instructions. To further investigate this issue, a 4 (stimulus difficulty) $\times$ 2 (instruction type) ANOVA was performed on the subject and item means in each condition. As before, there were significant main effects of stimulus difficulty [$F_1(3,234) = 19.61$, $p < .001$; $F_2(3,68) = 8.92$, $p < .001$] and instruction condition [$F_1(1,78) = 593.21$, $p < .001$; $F_2(1,68) = 12{,}391.37$, $p < .001$]. There was also a significant interaction between stimulus difficulty and instruction type [$F_1(3,234) = 11.54$, $p < .001$; $F_2(3,68) = 8.50$, $p < .001$].

As before, to analyze the interaction further, independent sample *t* tests were performed on the sizes of the effects of stimulus difficulty on naming latency for the two sets of instructions (external cue and internal timing). There was a nonsignificant effect of instruction type on the difference between high- and medium-frequency words, but there were significant effects of instruction type on the difference between medium- and low-frequency words [$t_1(78) = 2.70$, $p < .01$; $t_2(22) = 2.12$, $p < .05$] and low-frequency words and nonwords [$t_1(78) = 2.59$, $p < .01$; $t_2(46) = 1.98$, $p < .05$].

Discussion

As in Experiment 1, in the speeded condition, the ordinal relationships between the means of the naming latencies to the four stimulus types followed the pattern predicted by the relative frequency of the items. Thus, the assumptions made about the processing difficulty of these stimuli were validated. In addition, an inspection of the mean naming latencies shows that naming responses to the stimuli used here are typically made in less than 1 sec. This is an important point, because we are arguing that processing should be complete by that time.

Also as in Experiment 1, the internal-timing condition in Experiment 2 showed that the production of time intervals is influenced by the difficulty of a concurrently performed naming task, with intervals produced while a more difficult stimulus was processed being longer than intervals produced while an easier stimulus was processed. Therefore, the time perception hypothesis is supported. Thus, the use of a time criterion, and the time perception processes that accompany its use, may be an important underlying source of differences in naming latencies for different stimulus types.

Also as in Experiment 1, there was a significant interaction between stimulus difficulty and instruction type when the external cue and internal-timing conditions were considered. Thus, the effects in the internal-timing condition cannot be explained solely in terms of articulatory differences or other late-stage processes.

The main difference between the results of Experiments 1 and 2 was that there was a significant interaction between stimulus difficulty and instruction type when response latencies in the speeded and the internal-timing conditions were compared in Experiment 2, a difference that was not found in Experiment 1. Thus, it does appear that the internal-timing condition does not perfectly mirror what is going on in the speeded condition in the naming task.

The reason this interaction arose was due to a difference in the size of the contrast between low-frequency words and nonwords. Specifically, this contrast was significantly larger in the speeded instruction condition. Thus, it seems unlikely that one would be able to account for the differences among means in these two conditions entirely in terms of timing operations. Rather, some other process(es) seems to be at work to delay nonword naming latencies to a level beyond that expected on the basis of the timing operations demonstrated in the internal-timing condition. Possible explanations for this difference will be considered in the General Discussion section.

Despite this difference, a comparison of the latencies for the three word conditions shows parallel results of stimulus difficulty under speeded and internal-timing instructions, suggesting that similar processes are operating during word naming in these two tasks. What should also be noted, of course, is that external cue instructions did produce some evidence of effects of stimulus difficulty on naming latency. Thus, articulatory differences among our stimulus sets do appear to exist. However, they would be expected to affect performance in all three instruction conditions equally, and so they cannot be the source of interactions between stimulus type and instruction conditions.

As with the lexical decision task, it appears as though, in the naming task, different processes were operating in the external cue condition and the other two conditions and that reasonably similar processes appear to have been operating in the speeded and internal-timing conditions. This result supports the idea that time perception effects, in conjunction with the use of a time criterion, may provide a reasonable explanation of the effects of stimulus difficulty on response times in speeded word recognition tasks.

The core empirical point that we are attempting to establish here is that processing difficulty is a crucial determinant of perceived duration. By examining the effects of stimulus difficulty, we can see that the results of the internal-timing conditions showed that the perceived durations did follow the pattern predicted by differences in processing difficulty for different stimulus types found in these tasks under typical speed and accuracy instructions. Of course, processing difficulty also differs in terms of the task itself, which permits an examination of this issue in a somewhat different, and complementary, way.

Typically, latencies and frequency effects in lexical decision tend to be larger than those in naming (e.g., Balota & Chumbley, 1984), suggesting that the lexical decision task tends to be more difficult overall than the naming task and that frequency creates more of a processing difference gradient in lexical decision than in naming. Thus, under internal-timing instructions, one would expect that response latencies would be longer and effect sizes would be larger in our lexical decision task than in our naming task (i.e., when the lexical decision and naming internal-timing results are compared) if the differences in timing latencies are, indeed, produced by differences in processing difficulty.

A 4 (stimulus difficulty) × 2 (task) ANOVA contrasting the response latencies in Experiments 1 and 2 in the internal-timing conditions showed both a significant effect of task [$F_1(1,68) = 11.82$, $p < .01$; $F_2(1,68) = 197.91$, $p < .001$], with the lexical decision latencies being longer, and a significant interaction between task and stimulus difficulty [$F_1(3,204) = 15.65$, $p < .001$; $F_2(3,68) = 10.99$, $p < .001$], with larger stimulus difficulty effects in the lexical decision task [for the other main effect, stimulus difficulty, $F_1(1,68) = 134.03$, $p < .001$; $F_2(3,68) = 32.50$, $p < .001$]. This analysis provides further evidence supporting an explanation for latency differences to different stimulus types in terms of differences in time perception and the use of a time criterion.

GENERAL DISCUSSION

The time-criterion account (Lupker et al., 1997) originated as an attempt to show that changes in naming latency for both easy and difficult items when presented alone versus when presented randomly mixed together was better conceptualized as an effect of using a time criterion to guide the initiation of articulation, rather than as a strategic change in the nature of processing (e.g., decreasing or increasing emphasis on the lexical route, in a dual-route model of reading). More recently, this account has been criticized on the grounds that within sets of randomly mixed easy and difficult items, it cannot explain main effects of stimulus difficulty (e.g., Kello & Plaut, 2000). For participants in any speeded response experiment to actually use a time criterion, however, they must have access to some mechanism that keeps track of the passage of time. Any alterations in the performance of that mechanism would influence observed latencies. The goal of the present research was to determine whether past research showing that timing estimates are affected by the processing difficulty of the presented letter string (e.g., Chastain & Ferraro, 1997; Warm & McCray, 1969) would generalize to a situation similar to the situation in speeded response tasks and, potentially, help explain main effects of stimulus difficulty that persist when easy and difficult items are presented randomly mixed together.

The data from the internal-timing conditions in Experiments 1 and 2 clearly indicate that timing operations are affected by the nature of the stimulus being processed, so that time appears to pass more slowly when a difficult stimulus is being processed (see also Chastain & Ferraro, 1997; Hochhaus et al., 1991; Warm & McCray, 1969). The implication is that latency differences between stimuli that differ in difficulty (e.g., words and nonwords) when they are presented in a random order could, at least in part, be due to a timing mechanism working at different rates of speed in the two cases (together with a single time criterion). Indeed, with one exception, the data in the internal-timing instruction conditions mirrored the data in the speeded instruction conditions. These results suggest that the use of a time criterion, along with changes in time perception, may be a major source of the stimulus difficulty effects in mixed sets of stimuli in both lexical decision and naming tasks.

In contrast, effects of stimulus difficulty produced in the external cue condition were significantly different from those same effects in the other two conditions (speeded and internal timing). This result suggests that the processing invoked due to internal-timing instructions (i.e., having participants generate response cues) is based on a different set of principles from those used in a typical delayed task (i.e., using external response cues). In addition, given that the two alternatives to the time perception hypothesis discussed here, information criterion accounts and the flexible time-criterion hypothesis, would predict that any stimulus difficulty differences found under internal-timing instructions would also emerge under external cue instructions, these results provide good support for a response process guided by time perception processes working in conjunction with a time criterion.

Specific Accounts

As a specific example of an information criterion account of stimulus type effects in word recognition, consider the input gain account proposed by Kello and Plaut (2000). This account has been successful at explaining a number of strategy effects in the naming task. The question here is whether there is any way in which this account could explain the fact that effect sizes were essentially identical in the speeded and the internal-timing conditions.

One key aspect of the input gain account is that alterations in input gain come about due to changes in the emphasis for speed. For example, by providing participants with an external cue that required a response at a point early in processing, Kello and Plaut (2000) did induce participants to respond significantly more quickly than under normal speeded response instructions. They interpreted the impact of their task's demands as altering input gain (essentially, altering how rapidly the processing system carries out its operations).

Although Kello and Plaut's (2000) account may be a good explanation of their results, it is difficult to see how such a mechanism might play any role here. The (internal) cue to respond in our internal-timing condition created no speed emphasis. Thus, there would be no reason to adjust input gain from what it was in the speeded condition. Since responses in the speeded condition were able to be given in less than 1 sec, all responses in the internal-timing condition would have been ready to be given before the 1-sec interval had elapsed. Thus, there would be no reason to expect the effects of stimulus difficulty on response latency to remain in the internal-timing condition.

The results reported here also address the viability of Lupker et al.'s (1997) original explanation for the main effect of stimulus difficulty in mixed sets of trials—namely, that the time criterion is flexible. According to this hypothesis, if participants are ready to respond to an easy stimulus well before the time criterion is reached, sometimes they might initiate their response early. As well, sometimes, participants may not be ready to initiate a response to difficult stimuli when the criterion is reached, and so they may delay responding. If participants actually do respond early or late for these reasons and this varies systematically with stimulus difficulty (e.g., the participants are more likely to have to delay their response when naming a nonword, and the participants are more likely to be able to respond early when naming a word), this would create latency differences between easy and difficult stimuli in mixed groups of items.

Although the present data do not deny the possibility that this sort of event will occur at times, this flexible time-criterion hypothesis also has problems with the results in our internal-timing condition. In the internal-timing versions of the tasks, the time criterion that was imposed required the participants to delay responding to a point after which processing should have been completed. Thus, the participants did not need to delay responding because of a difficult stimulus, nor should they have been willing to initiate responding before the time criterion was reached. Thus, even if a flexible time criterion were used under typical speed and accuracy instructions, there would be no reason to expect any effects in our internal-timing conditions. Thus, the idea that a flexible time criterion is the primary cause of latency differences for different stimulus types receives little support.

Time Monitoring in the Present Experiments

The internal-timing manipulation is a novel one in the word recognition literature (but see Fortin and colleagues' work [e.g., Fortin, Rousseau, Bourque, & Kirouac, 1993] for a similar manipulation in visual search and memory search tasks). Thus, there are inevitably questions concerning how participants actually handle such a task. Our assumption, throughout the article, has been that time monitoring and word processing are carried out in parallel. In essence, while participants are deciding on the most appropriate response to the stimulus, they are involved in a dual-task situation. This assumption is consistent with the typical assumptions and explanations contained in studies in which the effects of stimulus difficulty on time perception have been examined (e.g., Brown, 1985; Brown et al., 1992; Casini & Macar, 1997; Chastain & Ferraro, 1997; Hochhaus et al., 1991; Warm & McCray, 1969; and many others). An additional claim we are making is that participants are doing something quite similar (i.e., monitoring time as they process words) in standard speeded response tasks, a claim that receives support from the parallels between the results in our speeded and internal-timing conditions. In fact, the claim that time is being monitored while word processing is ongoing in standard speeded response tasks is a core assumption of our time-criterion account. Thus, from our perspective, there is no major distinction between the speeded and the internal-timing conditions. Both are dual-task situations.

From an information criterion perspective, however, the speeded condition would not necessarily be considered a dual-task situation.[2] That is, if one assumes that in speeded tasks, participants respond as soon as sufficient information has accumulated, it would not be necessary for them to monitor the passage of time. Thus, one could argue that the stimulus type effects observed in the internal-timing condition arose for different reasons than did those in speeded conditions. If so, the internal-timing effects would not reflect the processes that occur in typical speeded tasks, making the parallels between tasks irrelevant.

Interestingly, also from an information criterion perspective, one could attempt to explain the parallels between the speeded and the internal-timing conditions in a quite different way. One could argue that the participants do not monitor time in either the speeded condition or the internal-timing condition. Perhaps, what participants do in the internal-timing condition is to carry out the word recognition task by using an information criterion and then simply add a constant amount of time before pressing the button or naming the stimulus. Thus, the argument would be that participants do not allow time monitoring to play a role even in a situation in which they are explicitly instructed to do so.

An important question then becomes, is there direct independent evidence that time monitoring typically occurs during speeded task experiments? Indeed, there is. In particular, research on the effects of foreperiod duration on stimulus latencies provides nice support for the idea that participants are continually monitoring time during the performance of speeded tasks (e.g., Grosjean, Rosenbaum, & Elsinger, 2001; Niemi & Näätänen, 1981; Requin, Granjon, Durup, & Reynard, 1973; Stilitz, 1972). For example, Grosjean et al. examined the effect of changing the time at which a stimulus occurred, presenting it either earlier than expected or later than expected. When a stimulus was presented earlier than expected, latencies increased, and error rates decreased; when a stimulus was presented later than expected, latencies decreased, and error rates increased. Grosjean et al.'s results indicated that the participants monitored the passage of time starting at the point that the previous stimulus had been responded to and prepared to begin stimulus processing at the point at which they expected the next stimulus to appear.

In general, what the results from all these articles suggest is that time monitoring is an inevitable component of behavior in speeded tasks even when participants are not explicitly asked to monitor time. Thus, it seems unlikely that explicitly asking the participants to monitor time in our internal-timing conditions fundamentally changed the nature of the task from a single-task to a dual-task situation. It also seems unlikely that the participants could possibly have decided to ignore time in the precise situation in which they were explicitly asked to monitor it.

Implications for Speeded Response Tasks

If our analysis of the impact of timing operations on speeded lexical decision and naming tasks is correct, it has implications for the use of speeded response tasks in general. That is, latencies in speeded response tasks are typically interpreted as directly reflecting the time it takes, for example, to derive a phonological code of a certain quality in a naming task or to establish a viable orthographic or semantic code in a lexical decision task. The analysis offered here suggests that latencies (and error rates) are more properly understood as the product of word recognition processes (such as phonological code generation) interacting with a general decision-making process (e.g., the setting of a time criterion as a guide to initiate responding).

How might such a process work? Although considerations of timing processes typically play very little role in most theoretical accounts of speeded responding, one exception can be found in recent work by Mozer and colleagues (Mozer, Colagrosso, & Huber, 2002; Mozer, Kinoshita, & Davis, 2003). According to these ideas, the point in time at which a participant responds is based on an analysis of costs. One cost is the likelihood of giving an inaccurate response. This likelihood decreases monotonically with time. A second cost is the passage of time. The more time that passes, the greater the cost (a relationship that in the present versions of the model, is assumed to be linear). When the sum of these costs reaches a minimum, a response is made. Thus, there is, essentially, a balancing of the two cost sources. As a result, easy stimuli will often be responded to when the likelihood of a correct response is quite high, because the cost due to the passage of time has been, and still is, minimal (i.e., not much time has passed). The result is a low error rate. Difficult stimuli, on the other hand, will be responded to when there is still some likelihood of an incorrect response, because the cost due to time's passing has grown noticeably and is growing faster than the cost due to error likelihood is decreasing (i.e., the minimum total cost point has been reached). In essence, what the participant is doing is implicitly saying, "I may not be sure about this response, but the time has come when I have to make what I think is the correct response." The result is a somewhat higher error rate.

The model following from these ideas has had some success in explaining the differences due to presenting stimuli in sets of one stimulus type or in randomly mixed trials of easy and difficult items reported by Lupker and colleagues (Lupker et al., 1997; Lupker et al., 2003), as well as the more local context effects (i.e., trial-to-trial "sequential effects") reported by Taylor and Lupker (2001a). One seemingly straightforward way to incorporate the effects reported here would be to assume that the slope of the function relating time to cost would vary as a function of the difficulty of the stimulus being processed. In particular, because time is perceived to pass faster when the stimulus is easy, the slope of the time cost function would be larger for easy stimuli.

Of course, there may be other ways of working the idea of changes in time perception into Mozer and colleagues' (Mozer, Colagrosso, & Huber, 2002; Mozer, Kinoshita, & Davis, 2003) model, and our argument is not that the differential-slope assumption must be adopted. Nor is it our argument that the model itself is necessarily correct. Note, for instance, that it does not incorporate the notion of a time criterion per se, a pillar of our theoretical position throughout this article. Rather, the argument is that the present data implicate models that acknowledge the importance of timing processes in determining when a speeded response is given. Only models of that sort would appear to have simple ways of explaining the present data.

An additional point that it is important to make is that we are not claiming that differences in response times are not due to differences in stimulus-processing difficulty. In fact, the claim is that differences in both response latency and the perception of the passage of time are due to differences in the difficulty of stimulus processing. A similar view is reflected in Chastain and Ferraro's (1997) examination of timing differences based on word difficulty, in which they argue that timing differences are an excellent way of assessing the difficulty of a stimulus (see also Fortin & Rousseau, 1987). In fact, measuring differences in time perception may be a more direct way of assessing processing difficulty than are some of the more standard experimental tasks, tasks that may allow for the introduction of strategic effects. Whether this proposal is correct or not, what we are suggesting is that results in speeded word recognition tasks are all *indirect* reflections of stimulus difficulty, rather than directly reflecting the time necessary to complete a certain amount of processing, and that factors that influence time perception very likely do impact response latency in speeded tasks.

Differences Between Low-Frequency Words and Nonwords in Naming

One remaining issue is the question of why there was a much larger difference between low-frequency words and nonwords in the speeded than in the internal-timing condition in the naming task (whereas there was no such difference when the same conditions were compared in the lexical decision task). The fact that there was no significant difference in response latencies to low-frequency words and nonwords in naming for the external cue condition suggests that this is not an effect due to processes that occur after responses have been initiated (e.g., Balota & Abrams, 1995). One possible reason for the speeded versus the internal-timing difference is that nonword naming may involve an extra process that occurs before response initiation that delays responding in a standard task (i.e., our speeded condition) but does not contribute to subjective difficulty and, therefore, is not reflected in subjective estimates of time. A second possibility is that there is a processing difference between words and nonwords that does influence actual response difficulty but does not influence time perception processes.

Obviously, there is a difference in the processing of words versus nonwords (at least, a quantitative difference in processing difficulty) that *does* influence time perception processes. However, although the commonly held view is that stimulus difficulty effects on time perception are due to the fact that a very general pool of *attentional resources* are shared between time perception processes and other, nontemporal processors (e.g., Block & Zakay, 1997), Fortin et al. (1993) showed that not all differences in processing difficulty influence time perception to the same extent. Thus, if Fortin et al. are correct, it is possible that a difference in the processing of words versus nonwords (particularly, according to Fortin et al., a difference that does not involve short-term memory) could influence response latencies but not time perception processes. In either case (whether or not the processing difference between words and nonwords does or does not influence subjective difficulty), this process would have to be one that can be at least partially performed prior to the 1-sec interval's elapsing, so that the difference between naming latencies to words and nonwords is decreased in the internal-timing condition, in comparison with the speeded condition. Presumably, this process would be late in the chain of processes involved in naming.

One candidate for such a late-stage process would be the process of generating an articulatory code (i.e., turning a phonological code into an articulatory code). This process may be something that is much more quickly done when the code is one that has been prepared before. In essence, the code may arise essentially automatically with words, but not with nonwords. In a naming task under speeded response instructions, this difference would create an additional delay in nonword naming. In our internal-timing and external cue conditions, however, the process could be accomplished during the waiting interval, leading to an overall smaller word–nonword difference. A second candidate would be the process that we have referred to as *lexical checking* (Kinoshita & Lupker, 2003; Lupker et al., 1997; see also Borowsky, Owen, & Masson, 2002). When there are a large proportion of words in the stimulus list, participants may try to avoid making errors in naming by checking their phonological output lexicon to make sure that what they are about to say is contained in that lexicon (i.e., does it sound like a word?). When the stimulus is a word, the checking process yields a quick match. However, when it is a nonword, the checking process is not only time consuming, but also unsuccessful. Engaging it would delay nonword naming in a speeded naming task; however, it might not do so when there is time between when the code has been generated and when it must yield a response, as in our internal-timing and external cue naming tasks. (Note also that neither generating articulatory codes nor checking the phonological lexicon would be involved in making lexical decisions. Hence, one would expect that the contrast between the speeded and the internal-timing conditions in the lexical decision experiment [Experiment 1] would not show this difference, just as has been reported.) Unfortunately, there is no way to adjudicate between these two explanations on the basis of the present data. Which will turn out to provide the better account of the present data remains a topic for future research.

Conclusions

The present set of experiments was designed to answer the empirical question of whether time perception varies as a function of processing difficulty in word-processing tasks and the theoretical question of whether it varies in a way that would allow the time-criterion hypothesis to explain main effects of stimulus difficulty on response latency that remain when easy and difficult items are mixed together and presented in a random order within one set of trials. Results from both naming and lexical decision tasks indicate that time perception does vary as a function of processing difficulty and that stimulus difficulty effects may, at least to a reasonable degree, be due to differences in how participants perceive the passage of time. These findings highlight the importance of examining the influence of nonlexical factors, such as criterion setting and the perception of the passage of time, when attempting to model and theorize about other psychological processes of interest.

REFERENCES

Balota, D. A., & Abrams, R. A. (1995). Mental chronometry: Beyond onset latencies in the lexical decision task. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **21**, 1289-1302.

Balota, D. A., & Chumbley, J. I. (1984). Are lexical decisions a good measure of lexical access? The role of word frequency in the neglected decision stage. *Journal of Experimental Psychology: Human Perception & Performance*, **10**, 340-357.

Balota, D. A., & Chumbley, J. I. (1985). The locus of word-frequency effects in the pronunciation task: Lexical access and/or production? *Journal of Memory & Language*, **24**, 89-106.

Baluch, B., & Besner, D. (1991). Visual word recognition: Evidence for strategic control of lexical and nonlexical routines in oral reading. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **17**, 644-652.

Block, R. A., & Zakay, D. (1997). Prospective and retrospective duration judgments: A meta-analytic review. *Psychonomic Bulletin & Review*, **4**, 184-197.

Borowsky, R., Owen, W. J., & Masson, M. E. J. (2002). Diagnostics of phonological lexical processing: Pseudohomophone naming advantages, disadvantages, and base-word frequency effects. *Memory & Cognition*, **30**, 969-987.

Brown, S. W. (1985). Time perception and attention: The effects of prospective versus retrospective paradigms and task demands on perceived duration. *Perception & Psychophysics*, **38**, 115-124.

Brown, S. W., Stubbs, D. A., & West, A. N. (1992). Attention, multiple timing, and psychophysical scaling of temporal judgments. In F. Macar, V. Pouthas, & W. J. Friedman (Eds.), *Time, action and cognition: Toward bridging the gap* (pp. 129-140). New York: Kluwer Academic/Plenum.

Casini, L., & Macar, F. (1997). Effects of attention manipulation on judgments of duration and of intensity in the visual modality. *Memory & Cognition*, **25**, 812-818.

Chastain, G., & Ferraro, F. R. (1997). Duration ratings as an index of processing resources required for cognitive tasks. *Journal of General Psychology*, **124**, 49-76.

Colombo, L., & Tabossi, P. (1992). Strategies and stress assignment: Evidence from a shallow orthography. In R. Frost & L. Katz (Eds.), *Orthography, phonology, morphology, and meaning* (pp. 319-340). Amsterdam: Elsevier.

Forster, K. I., & Chambers, S. M. (1973). Lexical access and naming time. *Journal of Verbal Learning & Verbal Behavior*, **12**, 627-635.

Fortin, C., & Rousseau, R. (1987). Time estimation as an index of processing demand in memory search. *Perception & Psychophysics*, **42**, 377-382.

FORTIN, C., ROUSSEAU, R., BOURQUE, P., & KIROUAC, E. (1993). Time estimation and concurrent nontemporal processing: Specific interference from short-term-memory demands. *Perception & Psychophysics*, **53**, 536-548.

GOLDINGER, S. D., AZUMA, T., ABRAMSON, M., & JAIN, P. (1997). Open wide and say "blah!": Attentional dynamics of delayed naming. *Journal of Memory & Language*, **37**, 190-216.

GROSJEAN, M., ROSENBAUM, D. A., & ELSINGER, C. (2001). Timing and reaction time. *Journal of Experimental Psychology: General*, **130**, 256-272.

HICKS, R. E., MILLER, G. W., & KINSBOURNE, M. (1976). Prospective and retrospective judgments of time as a function of amount of information processed. *American Journal of Psychology*, **89**, 719-730.

HOCHHAUS, L., SWANSON, L. G., & CARTER, A. L. (1991). Common words are longer in apparent duration than are rare words. *Journal of General Psychology*, **118**, 83-95.

KELLO, C. T., & PLAUT, D. C. (2000). Strategic control in word reading: Evidence from speeded responding in the tempo-naming task. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **26**, 719-750.

KINOSHITA, S., & LUPKER, S. J. (2003). Priming and attentional control of lexical and sublexical pathways in naming: A reevaluation. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **29**, 405-415.

KUČERA, H., & FRANCIS, W. N. (1967). *Computational analysis of present-day American English*. Providence, RI: Brown University Press.

LUPKER, S. J., BROWN, P., & COLOMBO, L. (1997). Strategic control in a naming task: Changing routes or changing deadlines? *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **23**, 570-590.

LUPKER, S. J., KINOSHITA, S., COLTHEART, M., & TAYLOR, T. E. (2003). Mixing costs and mixing benefits in naming words, pictures, and sums. *Journal of Memory & Language*, **49**, 556-575.

MCCLAIN, L. (1983). Interval estimation: Effect of processing demands on prospective and retrospective reports. *Perception & Psychophysics*, **34**, 185-189.

MCRAE, K., JARED, D., & SEIDENBERG, M. S. (1990). On the roles of frequency and lexical access in word naming. *Journal of Memory & Language*, **29**, 43-65.

MONSELL, S., PATTERSON, K. E., GRAHAM, A., HUGHES, C. H., & MILROY, R. (1992). Lexical and sublexical translation of spelling to sound: Strategic anticipation of lexical status. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **18**, 452-467.

MOZER, M. C., COLAGROSSO, M. D., & HUBER, D. E. (2002). A rational analysis of cognitive control in a speeded discrimination task. In T. Dietterich, S. Becker, & Z. Ghahramani (Eds.), *Advances in neural information processing systems* (Vol. 14, pp. 51-57). Cambridge, MA: MIT Press.

MOZER, M. C., KINOSHITA, S., & DAVIS, C. (2003, November). *Control and adaptation of the speed–accuracy tradeoff: A mathematical theory.* Paper presented at the 44th Annual Meeting of the Psychonomic Society, Vancouver.

NIEMI, P., & NÄÄTÄNEN, R. (1981). Foreperiod and simple reaction time. *Psychological Bulletin*, **89**, 133-162.

RASTLE, K., KINOSHITA, S., LUPKER, S. J., & COLTHEART, M. (2003). Cross-task strategic effects. *Memory & Cognition*, **31**, 867-876.

REQUIN, J., GRANJON, M., DURUP, H., & REYNARD, G. (1973). Effects of a timing signal on simple reaction time with a rectangular distribution of foreperiods. *Quarterly Journal of Experimental Psychology*, **25**, 344-353.

STILITZ, I. (1972). Conditional probability and components of RT in the variable foreperiod experiment. *Quarterly Journal of Experimental Psychology*, **24**, 159-168.

TABOSSI, P., & LAGHI, L. (1992). Semantic priming in the pronunciation of words in two writing systems: Italian and English. *Memory & Cognition*, **20**, 303-313.

TAYLOR, T. E., & LUPKER, S. J. (2001a). Sequential effects in naming: A time-criterion account. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **27**, 117-138.

TAYLOR, T. E., & LUPKER, S. J. (2001b, June). *Time perception and the naming task: Elaborating the time-criterion account.* Paper presented at the 10th Annual Meeting of the Canadian Society for Brain, Behaviour, and Cognitive Science, Quebec City.

THOMAS, E. A. C., & WEAVER, W. B. (1975). Cognitive processing and time perception. *Perception & Psychophysics*, **17**, 363-367.

WARM, J. S., & MCCRAY, R. E. (1969). Influence of word frequency and length on the apparent duration of tachistoscopic presentations. *Journal of Experimental Psychology*, **79**, 56-58.

NOTES

1. We are referring here to prospective, rather than retrospective, timing tasks. In both situations, participants are asked to give some measure of the length of an interval; however, the critical difference is whether the participants knew before the interval was presented whether they would be asked how much time had elapsed (prospective timing) or whether it was a "surprise" question at the end of the interval (retrospective timing). With respect to the present issues, if participants were using a time criterion in speeded response tasks, they would certainly know ahead of time that they would need to monitor the passage of time so that they would know when to respond. Therefore, retrospective timing results do not appear to be relevant to the present discussion.

2. The authors thank Chris Kello for bringing this issue to our attention.

APPENDIX

Words

High Frequency	Medium Frequency	Low Frequency
BLACK	BLAME	BLAND
BRING	BRAIN	BRACE
CHANGE	CHAIR	CHANT
DEAL	DECK	DEED
EACH	EAT	EEL
FEEL	FEES	FEAST
OLD	OAK	OATS
PLACE	PLUS	PLUCK
SEE	SEEK	SEEP
TAKE	TAPE	TAME
TAX	TASK	TAB
WELL	WET	WELD

Nonwords

ARB	ATH	BAME
BAMP	CABE	CARM
CHAND	CLAIL	DAND
FAMP	FASP	FEEB
FORP	GROACH	HARB
HOKE	HORCH	KEEM
LAS	LEB	LIBE
LOSK	MASP	MEK
OPE	PAIP	PASP
PLAMP	REAT	SEMP
STAM	TEP	THIM
TRAND	WAME	WIBE

Practice Stimuli

ELD	LATE	FEET	GUP
BEST	SKAL	TEST	YEAT

(Manuscript received February 18, 2004;
revision accepted for publication September 8, 2005.)