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Control Over the Time Course of Cognition in the Tempo-Naming Task

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Five experiments are reported in which standard naming and tempo-naming tasks were used to investigate mechanisms of control over the time course of lexical processing. The time course of processing was manipulated by asking participants to time their responses with an audiovisual metronome. As the tempo of the metronome increased, results showed that (a) the rate of lexical errors increased, whereas the rate of regularization errors remained constant; (b) onset errors increased at a faster rate than body errors; (c) stimulus effects weakened on latencies, whereas they strengthened on durations and errors; and (d) naming durations decreased more slowly when stimuli were presented prior to the response cue. These results constitute evidence that time pressure in the tempo-naming task caused a compression in the time course of lexical processing. Compression is discussed in terms of threshold mechanisms and rate mechanisms of control.

Lexical processes must be extremely flexible to accommodate the varied and innumerable tasks that a person encounters over time. For example, given the word *stop*, one must spell it when writing, rhyme with it in poetry and song, obey it when driving, remember it when studying a list of words, and so on. The diversity of these behaviors demonstrates how the access and usage of lexical knowledge is controlled according to task demands. The issue of control over lexical processing can be defined by three main research questions: (a) What are the mechanisms of control and how do they operate, (b) which aspects of lexical processing can be controlled and which cannot, and (c) what are the neural bases of control over lexical processing?

The current experiments were designed to address the first question in the context of a specific dimension of control in reading: the time course of lexical processing. Words take time to process, and the amount of time consumed by lexical processes on a given occasion can be influenced by the demands of the task. As an informal example, imagine that you are looking for your exit while driving on a busy highway at night. You catch a glimpse of an exit sign at the last minute, and you have only a moment to read the words and decide whether to maneuver toward the exit or pass the off ramp. The time pressure for an immediate decision in this situation places a demand on lexical processes (as well as decision processes) to work very quickly relative to their normal time course. Introspectively, it seems like the time course of processing can be shortened somehow in response to time pressure.

There is abundant evidence in support of this introspection. Many studies have examined speed–accuracy trade-offs in lexical processes by instructing subjects to respond more quickly or more slowly depending on the condition (e.g., Farrar, 1998; McElree, 1996; Stanovich & Bauer, 1978; Vitkovitch, Humphreys, & Lloyd-jones, 1993). In all of these studies, latencies decreased when instructions emphasized speed and increased when instructions emphasized accuracy. If one assumes that latencies reflect the time course of lexical processing, then pressure for fast responses (e.g., using a deadline procedure) must engage a control mechanism to shorten this time course. Similar evidence has come from stimulus composition studies in which difficult stimuli induce slower responses and easier stimuli induce faster responses (Jared, 1997; Lupker, Brown, & Colombo, 1997; Taylor & Lupker, 2001). However, in stimulus composition studies, a speed–accuracy trade-off is not always observed.

Although there is strong evidence for mechanisms of control over the time course of lexical processes, little is known about the specifics of these mechanisms. The purpose of the current study was to use a behavioral method called the *tempo-naming task* (Kello & Plaut, 2000) to investigate the nature of control over the time course of lexical processes. In the next two sections, two general classes of control mechanisms are discussed, *threshold mechanisms* and *rate mechanisms.* Control over the time course of lexical processing has usually been theorized in terms of threshold mechanisms, but Kello and Plaut (2000, 2003) proposed a rate mechanism termed *input gain* as an alternative to threshold mechanisms. Five experiments are reported here that were designed to test some predictions motivated by the hypothesis of a rate mechanism. The findings were consistent with the workings of a rate mechanism, but they also could be accommodated by threshold mechanisms under certain assumptions. The current experiments highlight the need to make three claims explicit when theorizing about data from speeded responses to words: What is the theory of lexical processing, what are the operative mechanisms of control over the time course of processing, and how is behavior driven by lexical processes?

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Threshold Mechanisms

The defining characteristic of threshold mechanisms is that they control the time course of processing by gating the flow of information from one level of processing to the next. The basic premise behind threshold mechanisms is that cognitive representations are gradually activated over time as information flows into a given level of processing. As activations increase, the representations can begin to affect "downstream" levels of processing. The question is, exactly when does information start to flow downstream (see, e.g., McClelland, 1979)? Threshold mechanisms play a role in determining this hypothesized point in time.

One of the most familiar types of threshold mechanism is an *activation criterion* (e.g., Ratcliff, 1978). An activation criterion controls the time course of processing by setting a threshold that at least one representation must exceed before information will flow downstream. Processing will have a slower time course when the activation criterion is relatively high because representations take time to activate, and a higher criterion will increase the time needed for information to flow downstream. Conversely, processing will have a faster time course when the activation criterion is lower. Moreover, lower criterion values will tend to cause errors in processing (i.e., a speed–accuracy trade-off) because low activation values will tend to reflect incomplete processing. *Baseline mechanisms* (e.g., Gratton et al., 1988) are effectively the same as threshold mechanisms in this respect. Baseline mechanisms adjust the overall activation values in a given level of processing. A low baseline is analogous to a high activation criterion because in either case, the distance that representations have to travel in terms of activation is relatively far.

Another type of threshold mechanism is a *time criterion* (e.g., Lupker et al., 1997; Swensson, 1972). A time criterion sets a time period relative to some starting point (e.g., stimulus onset), and information will not flow downstream until this time period has passed. A time criterion that is placed later in time will slow the time course of processing, similar to a high activation criterion. A time criterion placed earlier in time will have the opposite effect. If placed early enough in time, a time criterion can cause a speed–accuracy trade-off, as with a low activation criterion. Other types of threshold mechanisms include *derivative* thresholds, which require a process to stabilize to some criterion before information is allowed to flow, and *differentiation* thresholds, which require the activation of one representation to exceed the activations of other representations by some amount before information is allowed to flow. These mechanisms will influence the time course of processing in a manner similar to the activation and time criteria.

A defining feature of all threshold mechanisms is that they do not affect processing within the levels of representation that they govern. For example, in current models of word reading, activations are computed as a function of external inputs, internal sources of knowledge (e.g., connection weights or rules), and recent states of processing (e.g., priming). Activations are not computed as a function of thresholds. This point can be made clear by plotting a few illustrative activation curves over the time course of processing.

In Figure 1, two competing representations are shown to increase in activation early in the time course of processing. After some time, the incorrect representation is suppressed in favor of the correct one. In the driving example given earlier, one can imagine that one curve represents the actual exit name and the other curve represents a different exit name that is in some way similar to the actual one.

In the left-hand graph, the two horizontal dashed lines represent two possible activation criteria, and the two vertical dashed lines represent two possible time criteria. If the activation criterion is too low or the time criterion is too early, then a fast but incorrect response will be generated. The growth of these activation curves (i.e., their derivatives) is not a function of the thresholds but of stimulus information, knowledge, and context. The consequence is that threshold mechanisms do not directly interact with processing. Instead, they indirectly affect processing by gating the flow of information across levels of processing.

Rate Mechanisms

Rate mechanisms are the logical alternatives to threshold mechanisms. Rather than gating the flow of information, a rate mechanism influences the time course of processing directly by modulating the growth of activations. Kello and Plaut (2003) proposed and implemented one type of rate mechanism, termed *input gain.* In any input–output function, input gain can be defined as a parameter that modulates the function's sensitivity to its inputs. At low levels of input gain, the function is insensitive because large

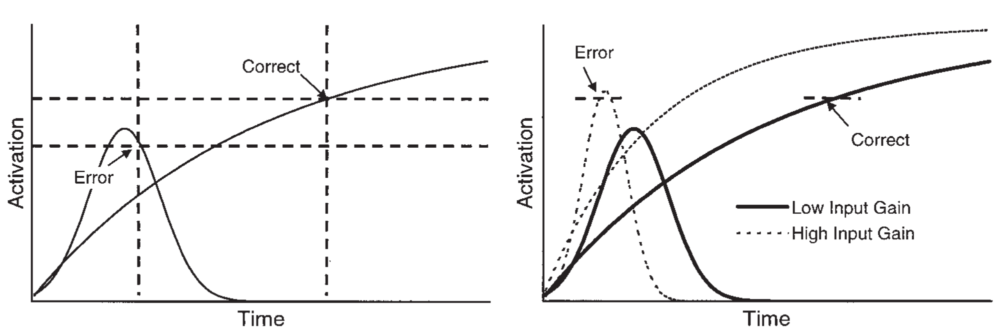

Figure 1. Illustrative examples of threshold mechanisms (left) and a rate mechanism (right). In the left graph, the horizontal dashed lines are activation criteria, and the vertical dashed lines are time criteria. In each graph, activation curves for two illustrative competing representations are plotted as a function of time from stimulus onset.

differences in the input correspond to relatively small differences in the output. At high levels of input gain, the opposite is true. For example, a common engineering usage of input gain is to modulate the sensitivity of a microphone. Low levels of input gain will cause the microphone to transmit a relatively quiet signal, whereas high levels will amplify the signal.

In connectionist models of cognitive processing, input gain has a natural implementation. Connectionist processing units take inputs and produce outputs. Each unit has an activation function that defines how inputs map onto outputs. Input gain can be implemented as a multiplicative scalar on the inputs to a processing unit. Inputs are usually summed to determine a given unit's output, and a net input of zero is often analogous to "cognitive silence," meaning no transmission of information by the processing unit. When zero net input corresponds to cognitive silence, the effect of input gain in a neural network will be analogous to its effect in a microphone. Large values of input gain will in some sense amplify the signals transmitted by the processing units (complications with this analogy are discussed later).

Given these basic properties of input gain, how can it modulate the time course of processing in a neural network? In some traditional types of connectionist processing units (e.g., the perceptron), outputs are computed instantaneously, in which case processing has no temporal extent. Input gain cannot modulate the time course of processing in models composed of such units because these models do not have a time course. However, the inputs or outputs of processing units can be integrated over iterations of processing. In this case, input gain will affect the number of iterations it takes for units to reach their asymptotic outputs (Kello & Plaut, 2003). If cognitive representations are coded in the asymptotes of unit outputs (as they usually are), then high levels of input gain will usually lead to faster rates of processing because outputs will reach their asymptotes more quickly. This property of input gain is shown in the right-hand graph of Figure 1.

Also shown in Figure 1 is the idea that high levels of input gain can lead to response errors. Activation of the incorrect response is shown to be amplified more than activation of the correct response, leading to an error. This is an abstract depiction of the underlying principle that high levels of gain can distort the time course of processing, analogous to how an audio signal can be distorted when the volume control on an amplifier is set too high. In connectionist models, high levels of input gain would result in distortions because of nonlinearities in the activation function (see, e.g., Kello & Plaut, 2003). Nonlinear activation functions such as the logistic are used because of their computational power and because neural processes appear to have analogous nonlinearities.

Threshold Mechanisms Contrasted With Rate Mechanisms

The most important difference between threshold mechanisms and rate mechanisms, relative to the current study, is that threshold mechanisms gate the flow of activation from one level of processing to the next, whereas rate mechanisms alter the time course of activations within a level of processing. This difference is reflected in the different kinds of research questions that have been motivated by each type of control mechanism. The gating function of threshold mechanisms leads to questions about response times, and tradeoffs between response times and response accuracies. Threshold mechanisms do not lead to questions about response durations or the nature of response errors, because threshold mechanisms are used to "release" responses for motor output. The time of release is assumed to govern the time to start a motor response, but not the time it takes to complete a motor response. Low thresholds are expected to lead to increases in response errors, but the kinds of response errors observed are not relevant to threshold mechanisms because thresholds do not interact with the processes they govern.

Rate mechanisms, by contrast, do lead to questions about response durations and the nature of response errors. If higher rates of processing compress the time course of lexical processing, then one might expect this compression to be reflected in the time course of responding. In other words, higher rates of processing might lead to shorter response durations, as well as faster response latencies. High levels of input gain would also be expected to cause a speed–accuracy trade-off, comparable to low thresholds. However, the interaction of input gain with lexical processing can lead to specific predictions about the kinds of errors one would expect at high gain, given the kinds of distortions that are caused by input gain.

To illustrate in more detail the contrast between threshold mechanisms and rate mechanisms, some previous studies are reviewed in the next two sections. Studies discussed in the first section were aimed at issues that arise from threshold mechanisms, and studies discussed in the second section were aimed at issues that arise from rate mechanisms. In both sections, it is argued that the results can be accounted for by either threshold or rate mechanisms. The purpose of these sections is to make explicit the parameters under which each class of mechanism can account for previous results.

Previous Experiments Aimed at Threshold Mechanisms

Most empirical work on control over time course has been associated with threshold mechanisms. For example, much of the work involving speed–accuracy trade-offs was theorized with threshold mechanisms, particularly for work with response deadlines (e.g., Farrar, 1998; McElree, 1996; Stanovich & Bauer, 1978; Vitkovitch et al., 1993). Response deadlines are typically implemented as follows. On each trial of a deadline task, a stimulus is presented, followed by response cue (e.g., a tone) after some delay. Participants are instructed to give their response as soon as they get the cue. By manipulating the delay between the stimulus and response cue, a speed–accuracy trade-off can be induced. More indirect methods such as monetary incentives for speed or accuracy were also used in some of the early work on control over the time course of processing (see Wickelgren, 1977).

It is easy to see how studies with response deadlines could be motivated by the concept of a threshold mechanism such as a time or activation criterion, and in fact, the results from such studies have been explainable on the basis of threshold mechanisms. However, rate mechanisms might also be used to account for the effects of response deadlines and speed–accuracy incentives. The basic idea is that pressure for speed would cause higher rates of processing (e.g., higher input gain), and pressure for accuracy would cause relatively lower rates of processing. For example, Kello and Plaut (2003) demonstrated how high levels of input gain can cause faster, more error-prone processing in two connectionist models of word reading. A high level of input gain caused more errors in those models because it distorted the time course of processing. It remains to be seen whether input gain might provide a more complete explanation of speed–accuracy trade-offs, but it currently appears to be a viable hypothesis.

Another type of effect that has been attributed to control over time course is the homogenization of latencies across trials of an experiment. Lupker and his colleagues have reported a number of studies in which the relative ease or difficulty of stimuli on previous trials affects the latencies on upcoming trials (Chateau & Lupker, 2003; Lupker et al., 1997; Taylor & Lupker, 2001). In particular, easier stimuli cause relatively shorter latencies on upcoming trials, and harder stimuli cause relatively longer latencies.

The authors have explained the homogenization of latencies with a time criterion mechanism. The idea is that easy stimuli allow for an early setting of the time criterion relative to the start of processing because easy stimuli are processed quickly. The converse is true for hard stimuli. Moreover, the time criterion is hypothesized to have inertia, such that its current setting will be influenced by its previous settings. On this account, previous settings should affect the latencies on upcoming trials, and latencies should tend to homogenize around the mean difficulty of stimuli in a block of trials. Both of these effects have been found.

However, as with speed–accuracy trade-offs, homogenization effects can also be explained with a rate mechanism. The rate of processing explanation is analogous to the time criterion explanation: Easy stimuli allow for high rates of processing, and hard stimuli require slower, more conservative rates. If the rate mechanism has inertia, then it should account for homogenization effects in the same way that a time criterion does. Consistent with this expectation, Kello and Plaut (2003) used input gain to simulate some of the homogenization effects reported by Lupker et al. (1997).

One question that arises is whether a rate mechanism would entail the prediction that naming durations should also show a homogenization effect, for the same reason that naming latencies show the effect. The answer is that this prediction depends on whether the time course of processing is reflected in the time course of articulation of the naming response. For instance, if response processing overlaps in time with response execution, then the time course of response processing should affect the time course of articulation. However, the amount of overlap is likely to depend on task-specific factors such as practice (Van Mier, Hulstijn, & Petersen, 1993) and time pressure (Kello, Plaut, & MacWhinney, 2000; Semjen & Garcia-Colera, 1986). It is also possible that there is more noise in response durations compared with response latencies. If so, a homogenization effect may be unreliable when measuring durations but reliable when measuring response latencies. Both of these examples demonstrate how a prediction about homogenization effects in naming durations is difficult to make without knowing more about when naming durations do and do not reflect the time course of processing.

Previous Experiments Aimed at Rate Mechanisms

As discussed earlier, rate mechanisms lead to questions about response durations and the nature of response errors. To address these kinds of questions, a methodology is needed in which the rate mechanism can be engaged and response durations and response errors can be observed. Kello and Plaut (2000) devised the tempo-naming task in response to this need. In the tempo-naming task, an audiovisual metronome is used to experimentally control the time course of processing and behavior. On each trial, a participant is presented with some number of beats of the metronome, and a stimulus (e.g., a printed word) is presented in time with the penultimate beat. The participant is asked to time her response (e.g., a naming response) with the last beat. The metronome effectively lets participants know exactly when they will have to respond to each stimulus well before the stimulus is presented. Kello and Plaut (2000) showed that the tempo-naming task affords fairly precise experimental control over response latencies through manipulation of the tempo of the metronome. Moreover, very fast tempos induced a speed–accuracy trade-off.

The audiovisual metronome allows for manipulation of rate of processing through manipulation of response latency. The naming response has the potential to reveal the influence of rate of processing, both qualitatively and quantitatively. Naming errors can reveal qualitative changes in the time course of processing because the contents of the naming response are open-ended. Naming durations can reveal quantitative changes in the time course of processing, provided that the time course of processing is reflected in the time course of articulation.

Kello and Plaut (2000) reported four experiments with the tempo-naming task, and they interpreted the results as consistent with the operation of a rate mechanism. With respect to response errors, results showed that lexicalization errors and nonword errors increased whereas regularization errors remained constant.[1] Lexicalization errors were word responses similar in form to the target (e.g., pronouncing *trick* as *think*), nonword errors were nonword responses similar in form to the target (e.g., pronouncing *shoe* as *shope*), and regularization errors were responses that incorrectly followed the spelling–sound correspondences for the target (e.g., pronouncing *pint* to rhyme with *mint*). In terms of a rate mechanism, these error results suggest that higher rates of processing weakened the contribution of spelling–sound correspondences on response generation, relative to other contributions such as those from words similar to the target (i.e., neighboring words). It is clear how neighboring words might lead to lexicalization errors, but they can also lead to nonword errors when the influence of two or more neighboring words is combined. For example, the words *shop* and *hoe* are neighbors to *shoe,* and their contributions might combine to generate *shope.* In summary, this interpretation of errors exemplifies an interaction between a rate mechanism and the time course of processing.

With respect to response durations, results showed that naming durations were compressed at the faster tempos. Naming durations were measured as the time from acoustic onset to acoustic offset of the naming response. This measure is a fairly good estimate of time elapsed from the start to the finish of the behavioral response (i.e., articulatory onset to offset). If one assumes that the time course of articulation had reflected the time course of processing in the tempo-naming experiments, then the compression of naming durations was evidence for a compression in the time course of processing. This interpretation is consistent with the operation of a rate mechanism because, as discussed earlier, higher rates of

[1] Kello and Plaut (2000) actually reported legitimate alternative reading of components errors (Strain, Patterson, Graham, & Hodges, 1998), of which regularization errors are a subset.

processing have the effect of compressing the time course of processing.

Results from the tempo-naming task have not yet been interpreted in terms of a threshold mechanism, but on inspection, it appears that such an interpretation could be formulated. For instance, one could hypothesize that faster tempos engage lower thresholds of some kind. A lower threshold would account for the observed speed–accuracy trade-offs at faster tempos. To account for the effect of tempo on error rates for different kinds of errors, one could posit the additional hypothesis that the contribution of spelling–sound correspondences is weaker earlier in the time course of processing. On this hypothesis, lower thresholds at the faster tempos would not cause an increase in the occurrence of regularization errors, which would be consistent with the data.

With respect to naming durations, there are two ways in which a threshold mechanism might be consistent with the observed compression of naming durations at faster tempos. On the one hand, it is possible that naming durations did not, in fact, reflect the time course of processing. In this case, the effect of tempo on naming durations could be explained as a purely motoric effect of responding quickly or slowly, and thus, threshold mechanisms would not be held accountable for the observed duration effects. On the other hand, it is possible that naming durations did, in fact, reflect the time course of processing. If so, a threshold mechanism would need to account for the observed duration effects. One way to account for these effects would be to allow a threshold to gate the flow of information in a continuous, cascaded manner. If the time course of articulation was cascaded with the time course of processing, then lower thresholds would result in faster rates of articulation (see Kello et al., 2000).

Current Experiments

The experimental results reviewed in the previous two sections do not appear to distinguish between threshold mechanisms and rate mechanisms. Speed–accuracy trade-offs and homogenization effects have been explained in terms of threshold mechanisms, and tempo-naming effects have been explained in terms of a rate mechanism. Nonetheless, the effects reported thus far can all be explained by either type of mechanism, at least in principle.

The purpose of the current experiments was to further investigate the control mechanisms engaged in the tempo-naming task. The experiments were designed primarily to determine whether the compression of naming durations at the faster tempos was due, at least in part, to a compression in the time course of processing. If so, we would have clearer evidence for the operation of either a rate mechanism or a cascaded threshold mechanism. The evidence would be clearer because standard threshold mechanisms cannot effect a compression in the time course of processing; they can halt the time course of processing, but the stopping point would have no bearing on the time course of response execution (i.e., naming durations). The experiments also provided more data on the kinds of errors produced at the faster tempos, using a wider range of items than those used by Kello and Plaut (2000). Although the kinds of errors observed will not provide unequivocal evidence for one control mechanism or the other, they will constrain the number of ways to explain the tempo-naming data. The possible explanations are elaborated on in the General Discussion.

For naming durations to provide evidence about the time course of processing, it must first be true that the time course of processing is reflected in the time course of articulation. The experiments reported by Kello and Plaut (2000) did not provide explicit evidence for such a relationship between processing and articulation. Therefore, the observed compression in durations may have been due to a purely motoric effect of responding quickly or slowly, rather than an increase in the rate of processing. For example, the motor system may get more “charged up” for faster tempos because of their perceived difficulty. This charge might cause naming durations to shorten, but it would not necessarily reflect a change in the time course of processing.

There were three ways in which the current experiments were used to test whether the time course of processing is reflected in the time course of articulation in the tempo-naming task. First, naming durations in the tempo-naming task were compared with naming durations in a delayed version of the tempo-naming task. In the delayed tempo-naming task, the target stimulus was presented at the beginning of each trial, and it remained on the screen for the duration of each trial. Thus, the task was similar to the standard delayed naming task in which a stimulus is presented and then followed by a response cue at some point later in time. Given that tempo-naming trials are relatively long in duration (e.g., 5,000 ms in the current experiments), the stimulus preview should provide ample time for all processing of the stimulus and response to be completed prior to the response cue, as in the standard delayed naming task. If the compression of naming durations at faster tempos is at least partly due to a motoric effect, then compression should be observed in both the delayed and the undelayed versions of the tempo-naming task. If the compression of naming durations is at least partly caused by a compression in the time course of processing, then the compressing effect of faster tempos should be weaker in the delayed tempo-naming task. The latter prediction is made because there is no pressure to compress the time course of processing in the delayed tempo-naming task.

The second way that the current experiments tested the relationship between the time course of processing and the time course of articulation was to examine stimulus effects on response latencies and response durations. If the time course of processing is reflected in the time course of articulation, then stimulus effects (e.g., printed frequency and spelling–sound regularity) should be reflected in response durations, for the same reason that stimulus effects are often reflected in response latencies. Stimulus effects on response durations have been found in some experiments (e.g., Kawamoto, Kello, Higareda, & Vu, 1999; Kawamoto, Kello, Jones, & Bame, 1998; Kello et al., 2000) but not others (Damian, 2003; Rastle, Harrington, Coltheart, & Palethorpe, 2000). Thus, it appears that the time course of processing is not always reflected in response durations.

There are many factors that may affect this relationship between processing and articulation (for a review, see Kello et al., 2000), but the one most relevant here is time pressure. A response can be initiated more quickly if response processing is allowed to overlap with response execution (i.e., one does not have to wait for the completion of processing). In fact, there is evidence that time pressure can increase the amount of overlap in time between response processing and response execution, thereby causing response durations to more clearly reflect the time course of processing (Kello et al., 2000; Semjen & Garcia-Colera, 1986). Moreover, an increase in overlap should *reduce* the extent to which response latencies reflect the time course of processing because there is a complementary relationship between latencies and durations in this respect. At one extreme, if response execution proceeds only after response processing is complete (i.e., no overlap), then only latencies will reflect stimulus effects. At the other extreme, if response execution is initiated simultaneously with the start of response processing (i.e., complete overlap), then only durations will reflect stimulus effects. Therefore, given that time pressure can increase the amount of overlap, one would expect stimulus effects to shift from response latencies to response durations at faster tempos. Such a shift was investigated in the current experiments as evidence for overlap between the time course of processing and the time course of articulation.

The third and final way that the current experiments tested the relationship between the time course of processing and the time course of articulation was to examine the locations of errors in naming responses. If processing overlaps in time with articulation, then there should be less time to compute the beginnings of responses (i.e., response onsets), compared with the ends of responses (i.e., response bodies). This is quite simply because the body of a response can continue to be processed while the onset of a response is being prepared and executed. The hypothesized time restriction on response onsets compared with response bodies predicts that faster tempos should cause a greater increase in onset error rates compared with body error rates. Note that this is not a prediction that participants are more likely to garble the articulation of onsets compared with bodies. Rather, onsets are predicted to be articulated intelligibly but incorrectly. This prediction was specifically tested in the current experiments.

To summarize, the relationship between the time course of processing and the time course of articulation was tested in the current experiments by (a) comparing response durations in delayed and undelayed versions of the tempo-naming task, (b) measuring stimulus effects on response latencies and durations as a function of tempo, and (c) comparing onset error rates with body error rates as a function of tempo. If these analyses show that the time course of processing is reflected in the time course of articulation, then the compression of response durations at faster tempos would stand as evidence for either a rate mechanism or a continuously gated threshold mechanism. The experiments also provided a more substantial database of errors in the tempo-naming task than provided by Kello and Plaut (2000). In the current study, this database was used to test whether difference in rates of lexicalization errors and regularization errors found by Kello and Plaut (2000) would replicate in a larger corpus of word stimuli. Error analyses such as these will provide different kinds of information, depending on whether a threshold mechanism or rate mechanism is engaged in the tempo-naming task. If a threshold mechanism is engaged, then the effect of faster tempos on errors will reflect representations activated early in the time course of processing. If a rate mechanism is engaged, then the effect of faster tempos on errors will reflect the distortion of representations caused by overly fast rates of processing.

Method

Five experiments were conducted. Experiment 1 was a standard naming task in which baseline stimulus effects were assessed. Experiment 2 was a tempo-naming experiment in which tempos were blocked. In Experiment 3, tempos were mixed. The blocking manipulation between Experiments 2 and 3 served to test whether the effect of tempo is due to the metronome on each trial or the overall *pace* of each block of trials. In all of the experiments reported by Kello and Plaut (2000), the tempos were always blocked. This blocked design made it unclear whether participants were able to adjust to the tempo on each trial or whether participants were only able to adjust to the overall speed of each block. The blocking of tempos was manipulated in the current experiments to clarify this ambiguity. Experiments 4 and 5 were delayed versions of the tempo-naming task, mixed and blocked, respectively. The delayed tempo-naming experiments served to test the degree to which the compression of naming durations at faster tempos is due to a motoric effect or a compression in the time course of processing.

Participants. Twenty undergraduates participated in each experiment (100 total). All reported being native English speakers with normal or corrected vision.

Stimuli. Six hundred words were sampled from a corpus of 3,427 English monosyllabic words. The goal of sampling was to preserve the distributional characteristics of the original corpus. This goal was set because it is well known that the composition of stimulus lists often has effects on behavior. However, list effects were not in the scope of the current experiments. Therefore, to minimize the potential for any biases in the stimulus lists to affect behavior, the distribution of stimuli was arranged so as to replicate the distribution of words in the normative reading environment. The words were selected by ordering the full corpus by printed frequency (as measured by frequency counts in the 1989 *Wall Street Journal* corpus; Penn Treebank Project, 1992). Approximately one out of every six words was chosen at regular intervals from the ordered list. Kello and Plaut (2003) showed that this method preserves at least some of the distributional characteristics of the original corpus.

One disadvantage to this sampling method is that it prohibits the grouping of stimuli for factorial designs (e.g., high and low frequency crossed with consistent and exceptional spelling–sound mappings). However, the hypotheses being tested by the current experiments required only an assessment of stimulus factors as a whole, not their factorialization. Therefore, it sufficed to code each item by a set of stimulus dimensions and then use these dimensions as independent factors in regression models to assess their influence on behavior.

Four dimensions of stimulus difficulty were chosen for the current experiments: printed frequency, orthographic neighborhood size, and spelling–sound consistency of both the onset and the body. Frequency was measured as the log of the *Wall Street Journal* frequency count. Orthographic neighborhood size was measured using Coltheart's *N.* Spelling–sound consistency was measured as the number of words that shared a given spelling–sound mapping divided by the total number of words that contained the given spelling. These counts were based on the monosyllabic corpus of 3,427 English words. As an example, for the word *shove,* the onset consistency was 1.0 because all words beginning in *sh* were pronounced with the same initial phoneme, and body consistency was .29 because the majority of words ending in *ove* do not rhyme with *shove.*

Stimulus dimensions such as these have been correlated with response latencies and error rates (Spieler & Balota, 1997). However, to use them as measures of processing difficulty, potential confounds must be taken into account. The confounds that probably account for the most variance in naming are the articulatory (and acoustic) features of the response (Kawamoto et al., 1998; Kessler, Treiman, & Mullennix, 2002; Rastle & Davis, 2002; Spieler & Balota, 1997). Articulatory features of the onset have been focused on the most because they are clearly relevant to measures of latency. However, when response durations are measured, it becomes necessary to take into account features of the entire response. This is because all parts of the response contribute to the duration of the entire response.

To address the need for articulatory features, the phoneme string that canonically described each stimulus was separated into an onset, a vowel, and a coda (with the possibility of a null onset or null coda). Each of these units was grouped according to the phonetic features of the constituent phonemes. There were 10 groups of onsets, 3 groups of vowels, and 15 groups of codas. The onset and coda groups were defined by the manner, voicing, and number of phonemes. The vowel groups were defined as short, long, and diphthong vowels. These codings were designed to help unconfound articulatory factors from the analyses of stimulus factors.

Procedure. Every participant saw all 600 words once, in random order. Across participants, stimuli were rotated among the tempos such that each stimulus appeared at each tempo twice for each experiment. All stimuli were presented as white characters on a black background in 48-point Times New Roman font. In Experiments 1, 3, and 5, there were 6 blocks of 100 trials each. In Experiments 2 and 4, there were 10 blocks of 60 trials each. Because tempo was blocked in Experiments 2 and 4, blocks were given in one of two orders, counterbalanced across participants. One order was 650, 550, 450, 350, 250, 600, 500, 400, 300, 200. The other order placed the multiples of 100 ms first. These orders were created to gradually increase the difficulty of the blocks over each half of the experiment. The tempos were chosen to induce a range of levels of time pressure, from very little to severe.

In Experiment 1, each trial began with a *Ready?* prompt that remained on the screen for a random amount of time between 800 ms and 2,800 ms. The random interval was created to prevent participants from falling into an intertrial rhythm. After the prompt, a fixation point was presented for 500 ms, followed by the target word, which remained on the screen for 1,500 ms. Participants were instructed to name the target word as quickly and accurately as possible. After each target word was removed, an intertrial interval was inserted such that the average trial duration was 5 s.

In Experiments 2–5, 10 tempos were tested between 200 ms and 650 ms, 50 ms apart. Each trial began with a *Ready?* prompt that included a visual scale that depicted the upcoming tempo (see Figure 2). The scale was a horizontal line with a vertical bisecting line in 1 of 10 positions. The left side of the scale was labeled *slow,* and the right side was labeled *fast.* The prompt and scale remained on the screen for a duration inversely proportional to the tempo for that trial, with faster tempos corresponding to longer durations. This duration scheme held the preparation time constant across tempos, and it held trial duration constant at 7 s. The prompt and scale were replaced by a fixation point for 500 ms. An audiovisual metronome followed the fixation point. Each tick of the metronome was a 70-ms beep, and each tick was accompanied by the removal of a visual flanker. Each trial began with five flankers, and they were removed from the outside inward. In Experiments 2 and 3, the target word was displayed in time with the fifth beat of the metronome (undelayed tempo naming). In Experiments 4 and 5, the target word was displayed with the prompt and scale, and it remained on the screen throughout the metronome (delayed tempo naming). Tempos were blocked in Experiments 2 and 4 and mixed in Experiments 3 and 5. Early and constant display of the target word enabled participants to prepare their response well before the sixth beat of the metronome.

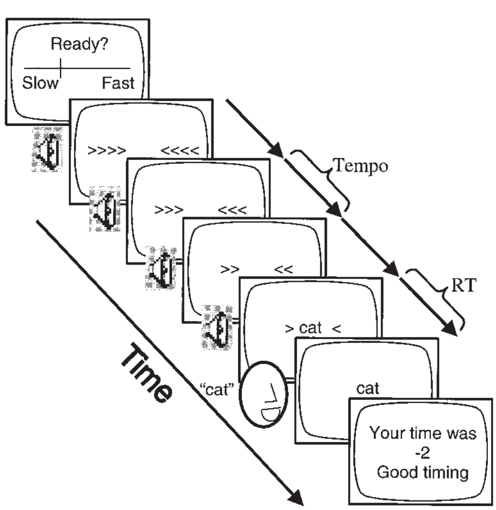

Figure 2. Diagram of the course of events for a single trial in the tempo-naming task. RT = response time.

Participants were instructed to time response initiation with the sixth beat of the metronome, even at the expense of errors. The last flanker was removed on the sixth beat, but without an accompanying beep. The target word remained on the screen for 1,500 ms. The target word was then replaced by feedback on response timing. Feedback was given as a number that equaled response latency minus tempo (in hundredths of a second): Negative numbers meant fast responses, positive numbers meant slow responses, and numbers close to zero meant well-timed responses. Numeric feedback was accompanied by one of the following phrases: *perfect timing, good timing, a little slow, a little fast, too slow,* or *too fast.* Feedback remained on the screen for a duration proportional to the tempo for that trial.

Apparatus and data analysis. Responses were collected and transduced using a Shure SM10A headset microphone, digitized using a Santa Cruz Turtle Beach sound card, and recorded to the hard drive of a PC computer running Windows 2000. Latencies were calculated online during the experiment using an algorithm similar to the one reported by Kello and Kawamoto (1998). These latencies were used for feedback in the tempo experiments. Afterward, response latencies and durations were hand-coded using a visual display of the response wave forms. Responses for which there were technical difficulties (less than 0.5% on average) were excluded from analyses. Technical difficulties included hardware and software failures and trials for which latency or duration was outside a normative range. For latencies, the normative range was 200 ms to 1,200 ms in the standard naming and tempo-naming tasks and 100 ms to 1,200 ms in the delayed tempo-naming task. For durations, the normative range was 100 ms to 1,200 ms for all tasks. All analyses are reported with subjects as the random factor; item analyses were not conducted because there were only two observations per item per tempo in each of the tempo-naming conditions.

Across all analyses, block order was not a reliable factor (except it was marginal in one analysis). Therefore, all analyses are collapsed across block order. Also, very few errors were made in the delayed-tempo task (1.7% averaged across Experiments 4 and 5). Errors in the delayed-tempo task are not discussed further.

Naming errors in the undelayed tempo-naming experiments were phonetically transcribed by undergraduates who were unaware of the research questions or hypotheses. The phonetic transcriptions were submitted to an algorithm for categorization. All errors were either articulatory in nature (e.g., a stutter or mis-start) or somehow similar to the target in terms of spelling or sound. The following five questions were asked of each error: (a) Was the error a word (e.g., *raise* pronounced as *rinse*), (b) was the onset a regularization (e.g., *gin* pronounced with a hard /g/), (c) was the body a regularization (e.g., *plaid* pronounced as *played*), (d) was the onset incorrect, and (e) was the vowel or coda incorrect? Errors were analyzed in terms of these distinctions, and all error results are reported in terms of the percentage (i.e., rate) of total number of responses. There was a total of 384 errors in Experiment 1 (standard naming), 1,525 errors in Experiment 2 (blocked tempo naming), and 1,568 errors in Experiment 3 (mixed tempo naming; there were virtually no errors in Experiments 4 and 5).[2]

[2] Stimuli and results (latencies, durations, and error transcriptions) for all participants in all five experiments are available for download at http://archlab.gmu.edu/cogdyn/downloads.

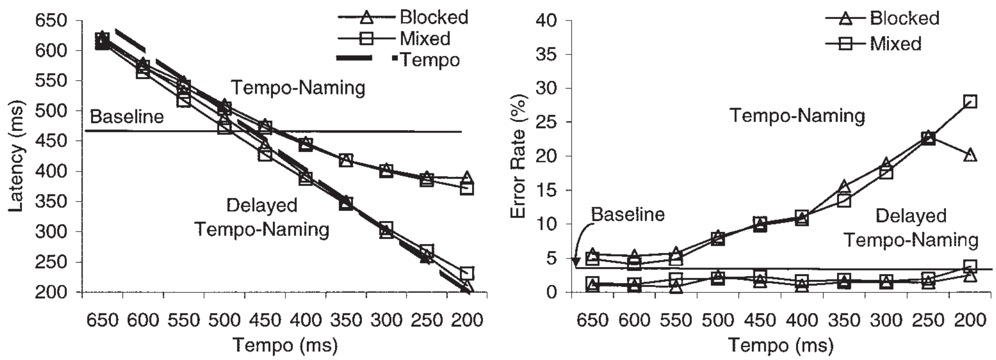

Figure 3. Subject means for latencies (left) and error rates (right) as a function of task, blocking, and tempo. The horizontal baselines show the mean latency and error rate from the standard naming task.

Results

On the left side of Figure 3, latencies are plotted as a function of task (tempo naming or delayed tempo naming), block condition (blocked or mixed), and tempo. As the graph makes clear, response initiation was increasingly delayed at the faster tempos in the tempo-naming task. This replicates the general effect of tempo on latencies that was found by Kello and Plaut (2000). By contrast, response initiation was well timed in the delayed tempo-naming task. This result shows that the large majority of timing error found in the tempo-naming task is attributable to the effect of time pressure on processing and not timing error per se. That said, there was a small but noticeable pattern of timing error in the delayed task: Latencies were slightly fast at the slower tempos and slightly slow at the faster tempos. This regression to the mean was also evident in latencies in the tempo-naming task. Therefore, a small portion of the inaccuracy in the timing of response can be attributed to timing error per se.

On the right side of Figure 3, error rates are plotted as a function of task, block condition, and tempo. As the graph makes clear, the tempo-naming task induced a speed–accuracy trade-off, whereas the delayed task did not. The observed speed–accuracy trade-off replicates the one that was found by Kello and Plaut (2000). The accuracy of naming in the delayed task, in terms of both response errors and response latencies, confirms that the stimulus preview had the desired effect of allowing for ample processing prior to response initiation.

With respect to the blocking manipulation, the graphs show that both latencies and error rates were comparable in the mixed versus blocked conditions. In fact, blocking had no reliable effect on latencies, durations, or error rates, nor did blocking interact with any other variable (all ps $> .10$).[3] The clear lack of a blocking effect shows that participants were able to adjust to the metronome on a trial-by-trial basis and that having a consistent tempo in each block did not help participants adjust to the metronome.

In Figure 4, naming durations are plotted as a function of task, collapsed across mixed and pure blocks. To recall, the primary purpose of examining durations was to test the degree to which the compression of naming durations at faster tempos is due to a motor effect or a compression in the time course of processing. If a motor effect contributes to the observed compression (e.g., owing to a "charging up" of the motor system), then naming durations should decrease with faster tempos in both the delayed and the undelayed tasks. If a compression in the time course of processing is involved, then naming durations should be shorter in the tempo-naming task, and more affected by the tempo, compared with the delayed tempo-naming task.

Results indicated that the compression of naming durations was attributable to both a motor effect and a compression in the time course of processing. In evidence of a motor effect, naming durations decreased with faster tempos in the delayed task, $F(1, 39) = 113.2$, $p < .001$, as well as the undelayed task, $F(1, 39) = 138.9$, $p < .001$. The effect of tempo in the delayed task can be interpreted as a motor effect because it cannot be interpreted as reflecting a compression in the time course of processing—that is, there was no time pressure to compress the time course of processing in the delayed tempo-naming task. By contrast, there was time pressure in the undelayed tempo-naming task, and results indicated that the time course of processing was compressed in response to time pressure.

Specifically, mean durations were shorter in the tempo-naming task, $t(78) = 3.55$, $p < .001$, and there was a reliable interaction of task and tempo, $F(3.9, 303.1) = 2.8$, $p < .05$.[4] Inspection of the task effect at each tempo indicates a nonmonotonic interaction such that task differences increased from 650 ms to 350 ms tempo but then decreased slightly from 350 ms to 200 ms tempo. The increase in task differences was most crucial to the current hypothesis, so the interaction was tested also over the tempos from 650 ms to 350 ms only. The linear divergence over these tempos was highly reliable, $F(1, 76) = 13.8$, $p < .001$, which is evidence that compression in the time course of processing had contributed

[3] It should be noted that at the fastest tempo, the mean error rate dropped in the blocked condition such that it was reliably less than that for the mixed condition (see Figure 3). It is unclear why this occurred, but one possibility is that some participants were frustrated by an entire block of impossibly fast tempos and reacted by somewhat relaxing their efforts to keep up with the tempo. The finding that latencies were slightly slower at the fastest tempo in the blocked condition is consistent with this hypothesis.

[4] Because the assumption of sphericity was not met, the Greenhouse–Geisser correction was used. This correction results in fractional degrees of freedom.

to the compression of naming durations in the tempo-naming task. The convergence in task differences between 350 ms and 250 ms can be explained as a floor effect on naming durations; that is, there are physical limits on how much a naming response can be shortened.

The effect of tempo on naming durations is one way to see the time course of processing reflected in the time course of articulation. Another way is to examine stimulus effects on naming latencies and durations as a function of tempo. If faster tempos cause more overlap in the time courses of processing and articulation, then stimulus effects should shift from response latencies to response durations at the faster tempos. To measure stimulus effects, regression analyses were conducted on the item means with naming latencies and durations as dependent measures, as well as error rates. Error rates were analyzed to confirm an effect that was expected in light of the trade-offs between speed and accuracy caused by faster tempos. Specifically, the effect of time pressure on error rates should be more severe for more difficult stimuli, regardless of the control mechanism engaged by time pressure. Therefore, one should expect stimulus effects on error rates to increase at the faster tempos.

In Table 1, the proportion of variance accounted for by stimulus factors is shown as a function of tempo, task, and dependent measure. For the undelayed version of the tempo-naming task, regression analyses are also broken down by tempo. Three groups of tempo were created for these analyses: slow (650 ms through 500 ms), medium (500 ms through 350 ms), and fast (350 ms through 200 ms). These groups were created to increase the statistical power of the regression analyses.

The R^2 values were generated from regression analyses conducted on the item means for each dependent measure. Four dimensions of stimulus difficulty (printed frequency, Coltheart's *N*, onset consistency, and body consistency; see *Stimuli* section) were entered simultaneously into each regression analysis as independent variables. The dependent variables were not the raw measures of latency, duration, and error rate but residuals of these measures after removing effects of the articulatory features of the response. Effects of articulatory features were removed by conducting analyses of variance on each dependent variable, with onset, vowel, and coda as the independent variables (see *Stimuli* section for how these were coded). Residuals were calculated by

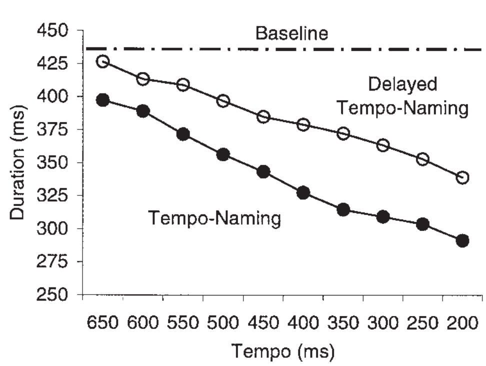

Figure 4. Subject means for naming durations as a function of tempo and task. The horizontal baseline shows the mean naming duration in the standard naming task.

Table 1

Proportions of Variance (R^2) Accounted for by Stimulus Factors for Naming Latency, Duration, and Error Rate

Task	Latency	Duration	Error rate
Standard naming	.163***	.020*	.090***
Delayed tempo	.002	.011	.026**
Undelayed tempo[a]	.095***	.021*	.186***
Slow	.067***	.007	.132***
Medium	.069***	.014	.153***
Fast	.051***	.045***	.160***

[a] Slow = 650–500 ms; medium = 500–350 ms; fast = 350–200 ms.
* $p < .05$. ** $p < .01$. *** $p < .001$.

removing the main effect of each independent variable (interaction terms were not included because these variables were not crossed factorially).

The R^2 values for the standard naming task and the delayed tempo-naming task served as points of comparison for the R^2 values in the undelayed tempo-naming task. In the standard naming task, stimulus factors were manifested most strongly in response latencies and less so in response errors. The opposite was true for data from the undelayed tempo-naming task. This pattern of R^2 values is evidence that, overall, there was more overlap between the time course of processing and the time course of articulation in the tempo-naming task as compared with the standard naming task. This was to be expected, given that the time pressure imposed by the metronome should be more severe than the self-regulated time pressure in the standard naming task. Moreover, there was evidence of more overlap at the faster tempos. Specifically, stimulus factors accounted for equal or less variance in response latencies, and more variance in response durations and error rates, at the faster tempos. Also, stimulus factors accounted for larger proportions of variance in response durations at the faster tempos.

The analyses of naming durations as a function of task, and the analyses of stimulus effects as a function of task and tempo, were primarily intended to examine how the time course of processing reflected in the time course of articulation. The third and final analysis intended for this purpose was a comparison of onset error rates versus body error rates as a function of tempo. If there is more overlap between the time course of processing and the time course of articulation at the faster tempos, then time pressure should have a more detrimental effect on response onsets compared with response bodies. In Figure 5, error rates for response onsets and response bodies are plotted as a function of tempo.[5]

The graph shows that at the slower tempos, body errors occurred more often than onset errors. At the faster tempos, this pattern reversed, such that onset errors occurred more often than body errors. The statistical reliability of this crossover in error rates was tested as follows. For each participant, onset error rates were computed at each tempo. Error rates were then regressed against tempo to compute a regression slope for each participant. The same was done for body error rates. As a result, each participant

[5] Articulatory errors such as stutters and mis-starts were not counted as onset errors.

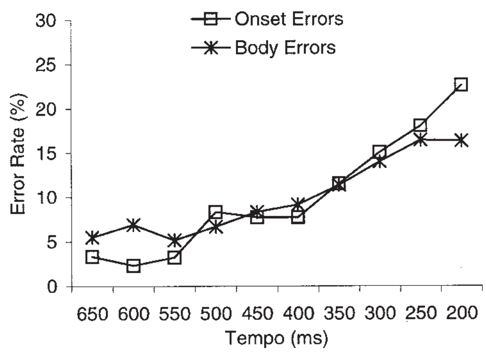

Figure 5. Mean error rates for onset errors and body errors plotted as a function of tempo.

generated a pair of regression slopes, one slope for onset errors and the other for body errors. A paired-samples t test was conducted on the participants' pairs of slopes, and the test showed that the slopes for onset error rates were steeper than those for body error rates, $t(39) = 3.1$, $p < .01$. This result, in addition to the effect of stimulus factors on response durations as a function of tempo, stands as evidence that articulation became more cascaded as tempos became faster.

The final issue to address is the rate of lexicalization errors compared with regularization errors as a function of tempo. Kello and Plaut (2000) used the pattern of errors as a function of tempo to examine the changes in processing under pressure for speed. Results showed that the rate of lexicalization errors, but not regularization errors, increased at faster tempos. These error results suggest that the contribution of spelling–sound correspondences to processing was weakened at the faster tempos relative to other contributions, such as those from neighboring words.

Lexicalization and regularization errors were examined in the tempo-naming experiments (Experiments 2 and 3) to test whether the error results from Kello and Plaut (2000) would be replicated in a larger set of word stimuli. In Figure 6, error rates are plotted as a function of tempo. The curves show that regularizations occurred less often as compared with lexicalizations and that only lexicalizations increased in number at faster tempos. The statistical reliability of the latter difference in error rates was tested as follows. For each participant, the number of lexicalizations at each tempo was computed in proportion to that participant's total number of lexicalization errors. The same was computed for regularizations. These proportions normalized for the overall difference in lexicalization rates compared with regularization rates. The proportions were regressed against tempo to compute two regression slopes for each participant, one for lexicalizations and one for regularizations. A paired-samples t test showed that the slopes for lexicalizations were steeper than those for regularizations, $t(39) = 5.0$, $p < .001$.

This result shows that the pattern of errors observed in Kello and Plaut (2000) was replicated in Experiments 2 and 3. However, the result is difficult to interpret because the stimulus set provided more opportunities for lexicalizations: A regularized pronunciation was possible for about one out of every six words, whereas a lexicalization was possible on every word. To provide a stronger test of the observed pattern, the regression analysis was repeated using only the exception words in the stimulus set ($N = 93$). A paired-samples t test again showed that the slopes for lexicalizations were steeper than those for regularizations, $t(39) = 5.2$, $p < .001$. These analyses show that the difference in regularization error rates and lexicalization error rates was not an artifact of stimulus selection. They also show that the increase in onset error rates with faster tempos was not due to an increase in the rate of regularization errors.

General Discussion

The main finding of the current experiments was evidence that the time course of processing was compressed by time pressure exerted in the tempo-naming task. The evidence in support of this finding was threefold. Most directly, naming durations in the delayed tempo-naming task were more compressed by faster tempos than those in the undelayed tempo-naming task. This comparison showed that the time course of processing contributed to the compression in durations above and beyond a purely motoric effect. More indirectly, two analyses showed that time pressure caused an increase in the overlap between the time course of processing and the time course of articulation. This effect was shown in analyses of stimulus effects as a function of tempo and comparisons of onset error rates and body error rates as a function of tempo. This increase in overlap is one way that the time course of processing can be reflected in the time course of articulation, which is a prerequisite for using naming durations as a window into the time course of processing.

The second main finding of the current experiments was that the rates of regularization errors showed no evidence of increasing with faster tempos, whereas the rates of lexicalization errors clearly increased with faster tempos. This pattern of error rates replicates those found by Kello and Plaut (2000), but in a larger corpus of word stimuli. One can assume that regularization errors are caused mostly by the misapplication of spelling–sound correspondences and lexicalization errors are caused by other factors such as lexical neighborhoods. Given these assumptions, the observed pattern of error rates suggests that the contribution of spelling–sound correspondences to processing was weakened at the faster tempos relative to contributions from other sources, such as neighboring words.

These findings have implications for the mechanisms of control engaged by tempo naming and for theories of lexical processing.

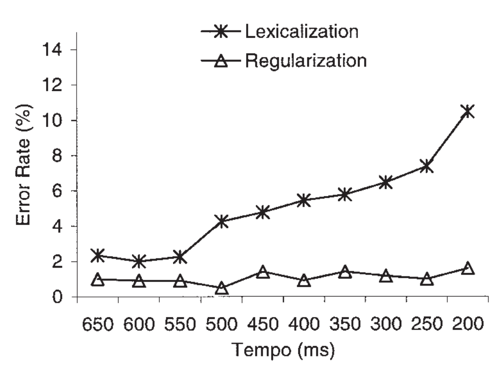

Figure 6. Subject mean error rates for lexicalizations and regularizations plotted as a function of tempo.

However, before these implications are discussed, an important issue must first be raised with regard to the idea of overlap between the time course of processing and the time course of articulation.

Cascaded Articulation and Anticipatory Coarticulation

Kello and his colleagues (Kello et al., 2000) referred to the idea of overlap between the time course of processing and the time course of articulation as *cascaded articulation.* The primary source of evidence for cascaded articulation has been processing effects on response durations, particularly on durations of the initial phoneme of monosyllabic naming responses (Kawamoto et al., 1998, 1999). These duration effects have been interpreted as evidence that articulation can begin as soon as the initial portion of the response is activated (e.g., the onset), even if the vowel and coda have not been resolved.

This interpretation of duration effects on the initial phoneme is at odds with the phenomenon of anticipatory coarticulation. Anticipatory coarticulation occurs when movements of the articulators at a given moment in time are "colored" by the movements associated with upcoming segments (Amerman, Daniloff, & Moll, 1970; Daniloff & Moll, 1968). A well-known example is that in the word *spoon,* lip rounding for the vowel can be observed during frication of the /s/. Anticipatory coarticulation cannot occur unless the upcoming segments are at least partially specified at the time that coarticulation occurs. By contrast, if articulation can begin with only the initial segment(s) specified, then this would preclude the possibility of anticipatory coarticulation on the initial phoneme. How can the findings of duration effects and anticipatory coarticulation be reconciled?

There are a number of possibilities. First, cascaded articulation is not the only way in which the time course of processing can be reflected in the time course of articulation. Processing may be completed before a response is initiated (i.e., no overlap), but the time course of past processing might be "imprinted" in the time course of subsequent articulations. Thus, the interpretation of naming durations as reflecting the time course of processing does not necessarily hinge on cascaded articulation.

Be that as it may, the current results indicated the articulation was, in fact, cascaded with processing in the tempo-naming task. If we assume that there was at least some amount of anticipatory coarticulation in the tempo-naming responses, then the duration results must be reconciled with anticipatory coarticulation. Three possible reconciliations are offered here. First, a response may be fully specified at the time of response initiation, but processing may continue into response execution. For example, a response may be initiated on the basis of a complete, but "quick and dirty," representation of the response. The processing that continues into response execution may serve to further refine this representation, thereby helping to monitor the response for errors and abort the response if necessary. The processing that is concurrent with response execution may cause a duration effect if a partial or tentative abort signal is generated due to processing difficulties. This account qualifies as a kind of cascaded articulation because response processing is ongoing during response execution. However, it does not posit response initiation without a representation of the entire response.

The second possible reconciliation is that each segment of a response may be partially, but not fully, specified at the time of response initiation. In the *spoon* example, one might imagine that the rounding for the vowel could be specified at response initiation but not its height. This would allow for anticipatory coarticulation, but if vowel height is not specified shortly after response initiation, then articulation of the onset might be stalled briefly to allow for processing to be completed. This stall would cause a duration effect that is simultaneous with anticipatory coarticulation.

The third possible answer is that some responses may show a duration effect without anticipatory coarticulation, and some responses may show anticipatory coarticulation without a duration effect. Although anticipatory coarticulation is common, if not fundamental, to speech production, it is not absolutely necessary (Whalen, 1990). It is therefore possible that responses with duration effects do not have anticipatory coarticulation. If this were the case, one would expect to simultaneously observe both duration effects and anticipatory coarticulation in averaged data. A test of this expectation has not yet been reported.

In summary, there are a number of ways to reconcile duration effects with anticipatory coarticulation, and studies thus far have not discriminated among them. For the current purposes, it is sufficient to say that cascaded articulation is at least plausible in the face of anticipatory coarticulation.

Threshold and Rate Mechanism Accounts

How might the results of the current experiments be accounted for by a threshold mechanism, and how would such an account differ from that of a rate mechanism? The first finding to consider is evidence for compression in the time course of processing at the faster tempos. As explained earlier, a threshold mechanism would have to be cascaded to effect a compression in the time course of processing; that is, it would have to gate the flow of information in a continuous, rather than an all-or-none, fashion. Moreover, articulation would have to be cascaded with time course of processing so that a faster flow of information could result in a faster rate of articulation. Most, if not all, extant threshold mechanisms are not cascaded, and hence, they cannot account for the data as currently formulated.

By contrast, the rate-of-processing mechanism provides a ready account of the observed compression in naming durations because higher rates of processing compress the time course of processing by definition. In support of this claim, Kello and Plaut (2003) showed how higher rates of processing, as implemented by input gain, would lead to faster naming latencies and shorter naming durations in connectionist models of word reading. This account must be based on the additional assumption that the time course of processing is reflected in the time course of articulation, for example, because of overlap in their respective time courses.

The next finding to consider is the shift of stimulus effects at faster tempos from response latencies to response durations. Either a cascaded threshold mechanism or a rate mechanism would presumably account for this shift, provided that the degree of cascading increased at the faster tempos. With more cascading, articulation would be initiated on the basis of less stimulus information, and hence, stimulus effects on naming latencies would decrease. The flow of stimulus information would be timed such that more of its impact would occur during the time course of articulation, and hence, stimulus effects on naming durations would increase.

Kello and his colleagues (Kello et al., 2000) demonstrated how a rate mechanism might cause a shift in stimulus effects off of response latencies and onto response errors and durations. They reported an abstract model of Stroop interference in which input gain was manipulated to control the time course of processing. At higher levels of input gain, the effect of Stroop interference decreased on response latencies but increased on response errors and durations. These results suggest that higher levels of input gain had caused a shift from a more staged to a more cascaded mode of processing. Similarly, one may be able to use input gain to account for the results with stimulus effects in the current experiments. However, the simulation reported by Kello and his colleagues was only an existence proof. Further simulation work is necessary to determine whether a rate mechanism could provide such an account in a model of word reading. A crucial aspect of this work will be to explicitly simulate the time course of processing and its relationship with the time course of behavior, something that has not been done in current models of word reading (in the models reported by Kello & Plaut, 2003, only the time course of processing was simulated).

The third and final finding to consider is the effect of tempo on response errors. Faster tempos caused a speed–accuracy trade-off, and, as explained in the introduction, both rate mechanisms and threshold mechanisms can be used to cause a speed–accuracy trade-off. However, neither type of mechanism can directly account for the effect that tempo had on the rates of different kinds of errors. The reason for this is that control mechanisms operate on lexical processes, and a response is always a function of control mechanisms in conjunction with the lexical processes themselves (among other factors). Whereas general measures of behavior such as mean latencies and overall error rates might be predictable on the basis of control mechanisms alone, the specific types of errors are not. To explain differences in rates of different error types, one must consider how control mechanisms operate in the context of a specific theory of word reading.

Two tests of error types were conducted in the current experiments. First, it was shown that the rate of lexicalizations, but not regularizations, increased at the faster tempos. This difference between error types suggests that the contribution of spelling–sound correspondences was weakened at the faster tempos. Kello and Plaut (2003) showed how input gain could have this effect in a connectionist model of word reading, but the effect depended on the architecture of the model. In a "triangle" model (see Plaut, McClelland, Seidenberg, & Patterson, 1996), input gain caused an increase in regularization errors, whereas it did not in a model with only one pathway from orthography. These simulations served to demonstrate that it is at least possible to use a rate mechanism to account for lexicalizations and regularizations in tempo naming. The simulations also served to demonstrate how errors depend on the control mechanisms as well as lexical processes.

The second test of error types in the current investigation was between onset errors and body errors. It was shown that the rate of onset errors increased more than that of body errors at the faster tempos. This difference between error types was interpreted as evidence for cascaded articulation, but for an explanation to be complete, ultimately it will need to refer to a theory of lexical processing. To illustrate, cascaded articulation may explain the difference in error types if the phonological representations are activated in parallel, as they are in distributed models of word reading (e.g., Plaut et al., 1996). Parallel activation may allow time for the body of the response to resolve during response preparation and initiation, thereby attenuating body errors relative to onset errors.

On another theory of lexical processing, phonological representations may be activated serially from left to right, as they are in the rule route of the dual-route cascade model (Coltheart, Curtis, Atkins, & Haller, 1993; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). It is not clear how left-to-right processing could account for the difference between onset errors and body errors. Combined with cascaded articulation, onsets should be less error prone as tempos get faster, because onsets are processed before bodies. However, the point here is not to use the error results to argue for one theory or another. The point is to illustrate how any account of error types in the tempo-naming task (or any naming task, for that matter) will require explicit claims about control mechanisms, as well as theories of word reading. Until such claims are made, the observed error types cannot be used to argue for threshold mechanisms versus rate mechanisms or for different theories of word reading.

Conclusions

In this study, it was argued that the time course of lexical processing was compressed in response to time pressure in the tempo-naming task. It is an open question whether effects of control over lexical processing in other tasks can also be theorized in terms of a compression in the time course of processing. For instance, the homogenization effects on response latencies found by Lupker and his colleagues were discussed earlier (Chateau & Lupker, 2003; Kinoshita & Lupker, 2003; Lupker et al., 1997; Taylor & Lupker, 2001). These researchers have explained homogenization effects in terms of homogenization in the setting of a time criterion, which is a type of threshold mechanism, but Kello and Plaut (2003) showed how homogenization in the rate of processing could similarly account for homogenization effects. Further research is necessary to determine whether a time criterion or rate mechanism (or some kind of cascaded threshold mechanism) is responsible for homogenization effects. One distinguishing characteristic is that a time criterion cannot predict accompanying duration effects, whereas a rate mechanism can, provided that there is overlap between the time course of processing and the time course of articulation. An investigation into this issue would therefore need to establish overlap in order to use duration effects to adjudicate between these types of mechanisms.

Threshold and rate mechanisms control the time course of processing, but other studies have investigated more attentional forms of control. Specifically, a number of researchers have proposed that different types of information or processing can be emphasized or deemphasized on the basis of task demands (Balota, Cortese, & Wenke, 2001; Balota, Law, & Zevin, 2000; Monsell et al., 1992; Rastle & Coltheart, 1999; Zevin & Balota, 2000). For instance, a series of nonword primes can slow down the latency to an upcoming exception word, and a series of exception words can slow down the latency to an upcoming nonword (Zevin & Balota, 2000). These and similar results have been interpreted as attentional control over lexical and sublexical processing pathways, although there is some debate as to whether such results actually reflect control over the time course of processing, rather than attentional control (Chateau & Lupker, 2003; Kinoshita & Lupker, 2003; Lupker et al., 1997).

Interestingly, the control mechanisms discussed in the current study could serve both as mechanisms of control over time course and mechanisms of attentional control. For example, if a very stringent threshold was set on a particular level of processing, then that level would have little or no influence on behavior, because its processing would never be transmitted to other parts of the system. This would effectively be a form of attentional gating. Similarly, rate of processing could be manipulated selectively over particular levels of representation. For example, Kello and Plaut (2003) manipulated input gain over two different processing pathways in a model of word reading. Simulated naming errors showed that input gain had functioned as a mechanism of attentional control. These ideas and results motivate further work to investigate a possible link between attentional control and control over the time course of processing.

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