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The Effects of Spatial Stimulus–Response Compatibility on Choice Time Production Accuracy and Variability

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Five experiments examined the relations between timing and attention using a choice time production task in which the latency of a spatial choice response is matched to a target interval (3 or 5 s). Experiments 1 and 2 indicated that spatial stimulus–response incompatibility increased nonscalar timing variability without affecting timing accuracy and that choice reaction time practice reduced choice time production variability. These data support a "temporal discounting" model in which response choice and timing occur in series, but the interval timed is shortened to account for nontemporal processing. In Experiment 3, feedback and anticipation task demands improved choice time production accuracy. In Experiments 4 and 5, the delay between the start-timing and choice-decision signals interacted with choice difficulty to affect choice time production accuracy and variability when timing a 3- but not a 5-s interval, suggesting that attention mediates timing before and after an interruption in timing.

Keywords: time perception, attention, reaction time, stimulus–response compatibility, scalar property of timing variability

In a time production task, participants match the latency of a simple motor response to a target time interval. To accomplish this match, response selection and execution must occur during the elapsing interval. The occurrence of these two processes during the interval suggests that the timing system ordinarily interacts with motor processes in a way that does not adversely affect timing accuracy. The question then arises as to the consequences of adding to, or changing, the dynamics of those motor processes. The present experiments addressed this question with a "choice time production" task that requires participants to time the execution of a multiple-alternative forced-choice spatial discrimination response. By varying the difficulty of the choice component of the task, insight may be gained about whether response choice and response timing mechanisms occur in series and, more generally, about how timing and attention interact.

Interactions between timing and attention first became apparent in studies in which the estimated duration of nontemporal tasks depended on the difficulty of the task (e.g., Brown, 1985, 1997; Hicks, Miller, & Kinsbourne, 1976; Macar, 1996; McClain, 1983; Zakay, Nitzan, & Glicksohn, 1983). More relevant to the present experiments are dual-task paradigms that combine explicit timing tasks with nontemporal cognitive processing tasks (e.g., Burle & Casini, 2001; Casini & Macar, 1997; Fortin & Breton, 1995; Fortin, Rousseau, Bourque, & Kirouac, 1993). In general, when a nontemporal secondary task is added to a prospective timing task subsequent to the initial learning of a given target interval, then that interval is judged to be shorter or is produced as longer than the target. The magnitude of these effects depends on the type and complexity of the secondary task as well as on the instructions regarding the relative allocation of attention to either task component (Macar, Grondin, & Casini, 1994).

An explanation of the effects of secondary task processing on time production has emerged from standard internal clock models of timing (Gibbon, 1977; Treisman, 1963). The internal clock's time basis consists of a pacemaker that emits pulses at regular intervals and an accumulator. The accumulator sums pacemaker pulses over time, yielding a value that can be stored in memory for later reference or compared with an existing memory for purposes of initiating or inhibiting time-dependent behavior. When attention is directed away from timing, a "switch" (in Scalar Expectancy Theory [SET]; Meck & Church, 1983) or "gate" (in the Attention Gate Model; Zakay & Block, 1997; cf. Lejeune, 1998) opens and prevents the pacemaker from exciting the accumulator. In cases in which a secondary task is added to a timing task, timing is distorted because the switch remains open while attention-demanding aspects of the secondary task is being processed. That is, all or part of the secondary task is processed in series with timing. As a result, the decision criteria expressed in terms of accumulator excitation is reached later, and the intervals produced are too long relative to the target interval.

Less frequently investigated are the effects of attention on timing variability. In general, Weber's law governs temporal psychophysics (Allan & Gibbon, 1991; Getty, 1975; Gibbon, Ma-

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lapani, Dale, & Gallistel, 1997; Ivry & Hazeltine, 1995; Kristofferson, 1976; Rakitin et al., 1998; Rakitin, Stern, & Malapani, 2005; Wearden & McShane, 1988). In time production, Weber's law is evident in approximately equal average response latency coefficients of variation (*CV*s), or the mean (*M*) divided by the standard deviation (*SD*), within a given task for production of different intervals. Weber's law applied to timing is also referred to as the *scalar property of timing variability*. SET attributes scalar variability to the pacemaker, memory, and decisions stages of the information-processing model described above (Gibbon & Church, 1984; Gibbon, Church, & Meck, 1984). Changes to the scalar property have been useful for detecting the effects of attention on timing in animal timing experiments (Gibbon & Church, 1984; Gibbon et al., 1984; Meck, 1984; Meck, 1991; Meck & Church, 1983).

If in dual-task time production an attention-demanding process that holds the switch open varies in duration, then the switch-open time will vary as well. As a consequence, the total dual-task timing variance will be the sum of the variance in the switch-open time and the variance from all other timing processes because the variance of independent processes in series sum. Dual-task timing can result in a violation of the scalar property because the variability in the switch-open time is nonscalar; that is, it is not related to the target interval duration. This violation occurs because a nonscalar source of variability is a larger proportion of the scalar variability in timing a short interval compared with a long interval. Consequently, one may predict that in dual-task time production, the *CV* of a short interval will be greater than the *CV* of a long interval. This effect is predictable to the extent that independent estimates of the dynamics of the timing and nontiming processes in the dual task can be obtained from basic time production and choice reaction time (RT) tasks, respectively.

A few studies of timing and attention have reported variance data. One study combining time production with a digit-naming task found an increase in timing variability in dual-task timing compared with timing alone (Perbal, Droit-Volet, Isingrini, & Pouthas, 2002). Consistent with the switch models, the *CV* was greatest for the shortest interval. Similarly, in a study of temporal stimulus–response (s-r) compatibility, the *CV* was higher for production of a short interval following a long cue (36.1%) than for production of a long interval following a short cue (23.0%; Grosjean & Mordkoff, 2001, Table 2). Studies of timing that explore attention to more than one timing signal (Lustig & Meck, 2001; Penney, Gibbon, & Meck, 2000; Vanneste & Pouthas, 1999) also noted increased timing variability, although these effects were attributed to memory and clock-speed effects rather than to the effects of attention on the switch.

The present experiments narrow the issue of attention and timing to the question of how the addition of response choices of varying difficulty and the requirement of different degrees of attention affect timing. Manipulating the spatial compatibility of the stimulus and response sets (or spatial s-r compatibility; Fitts & Deininger, 1954; Fitts & Seeger, 1953; Keele, 1986; Kornblum & Lee, 1995) is one way to vary response choice difficulty. The three choice-difficulty conditions in the present experiments, in order of increasing difficulty, are (a) a "simple" condition in which there is no choice of keys; (b) an "incompatible" s-r condition in which the locations of the response keys are determined from the location of the stimuli, plus a memorized set of rules; and (c) a "compatible" s-r condition in which the locations of the response keys correspond directly to the locations of the stimuli.

Spatial compatibility manipulation has several features that are advantageous to the present investigations. First, the well-studied spatial compatibility manipulations are known to result in changes to response selection and response execution mechanisms (Keele, 1986; Kornblum & Lee, 1995; Lien & Proctor, 2002), necessarily part of any production task. Second, spatial compatibility manipulations in studies of the psychological refractory period (PRP; Lien & Proctor, 2002; Pashler, 1994; Pashler & Johnston, 1989; Van Selst & Jolicoeur, 1997) indicate that response selection requires attention. Third, increasing spatial incompatibility in choice RT tasks produces large and reliable increases in RT means (for a review, see Teichner & Krebs, 1974). Finally, spatial incompatibility increases intraparticipant RT variability, even accounting for the increased mean RT (i.e., the *CV* of RT; Grosjean & Mordkoff, 2001). These facts increase the likelihood that spatial s-r compatibility interference with timing will be of a detectable magnitude.

In Experiment 1, the hypothesis that response choice and response timing occur in series was tested by examining the effects of choice difficulty on the new choice time production task. The assumption is that for a given choice condition, the choice RT predicts the switch-open time in the choice time production task. If so, then one may expect a larger choice time production mean and *CV* and violations of the scalar property in the more difficult choice conditions. In Experiment 2, the serial hypothesis was tested further by asking whether for one choice-difficulty condition, the choice time production mean and *CV* differ because of choice RT practice. The new "temporal discounting" model was used in Experiments 1 and 2. This model extends the standard switch model to include an error correction process in order to show that increases in choice time production variability are consistent with serial processing when changes to the mean response latency are smaller than expected.

The additional experiments reported here explored the effects of two aspects of Experiment 1 that differ from the typical experimental designs used to investigate the effects of attention on time production (e.g., Fortin & Breton, 1995; Fortin et al., 1993). By understanding the effects of omitting feedback (see Experiment 3) and splitting the response choice and timing cues (see Experiments 4 & 5) in the choice time production task, the results of Experiments 1 and 2 can be more easily integrated into the existing literature.

Experiment 1: Effects of Response Choice Difficulty on Production of Two Intervals

The present experiment introduced the choice time production task. Participants matched their response latencies to the duration of a target interval, as in a simple time production task. However, the timing signal also served as the imperative stimulus that indicated the identity of the response ultimately executed at the end of the target interval. The task is therefore a "dual task" in the sense that timing and response choice processes must occur within a single trial. The task differs from previous dual-task studies (e.g., Fortin & Breton, 1995; Fortin et al., 1993) in that there is just a single stimulus. An integrated stimulus helps to avoid the issue of whether the effects of the choice stimulus lie in the nontemporal cognition that occurs upon its appearance or in the interruption of the timing signal (Fortin, 2003; Fortin & Masse, 2000). Also, feedback is used to prevent drifting of response latency across the choice time production task and to create conditions favorable to detecting changes in response latency variability associated with attention under SET.

Method

Participants

Forty-one undergraduate students at the University of Oregon served as participants. They were recruited from department of psychology courses and were rewarded with credit toward completing course requirements. Of the participants, 5 were subsequently eliminated from analysis, 4 for failing to meet performance-based inclusion requirements, and 1 for failing to adhere to task instructions. (Exclusion criteria are given in the *Analysis* section, below.) Participants were assigned to one of three experimental choice difficulty groups: "simple," "compatible," or "incompatible."

Apparatus

Testing was conducted on an Apple Macintosh CI computer, equipped with a 13-in. (33-cm) Sony Trinitron color monitor, and an Apple Desktop Bus (ADB) keyboard. Responses were made on the ADB keyboard. This apparatus yielded a maximum response latency acquisition accuracy ±16 ms. Stimuli were presented on the color monitor, synchronized to the screen refresh. Stimulus presentation and response acquisition were driven by the PsyScope experimental design package, Version 1.1 (Cohen, MacWhinney, Flatt, & Provost, 1993).

Stimuli

The three different tasks used in this experiment shared a common warning signal array and stimulus. The warning signal array consisted of a central fixation point (a "+") and four place markers (a "_"). The fixation point and place markers were on a horizontal axis in the middle of the screen. Place markers and the fixation point were equally spaced 2.5 in. (6.4 cm) from each other. The left- and right-most place markers were 1.5 in. (3.8 cm) from the edge of the monitor's visible viewing region.

A stimulus was superimposed on the warning signal array after 500 ms. The stimulus was an "*X*" approximately 1 in. (3 cm) high × 3/4 in. (3 cm) wide. The stimulus appeared just above one of the four lines in the warning signal display. Both the stimulus and the warning signal array persisted until a response was made or until the trial timed out.

Feedback messages were presented 500 ms after the clearing of the warning signal array and the stimulus. Messages were presented in the center of the screen for 2 s.

Procedure

An experimental session for 1 participant consisted of two sequences of three different tasks. The tasks, in order of administration within a sequence, were (a) a choice RT task, (b) a simple time production task, and (c) a choice time production task. The two sequences differed in the simple time production and choice time production tasks' target interval duration. The target intervals were either 3 s or 5 s in duration. The assignment of target interval to sequence was counterbalanced across participants within the choice-difficulty groups. Choice-difficulty group affected the choice RT and choice time production tasks, as detailed below.

The choice RT task. In this task, participants selected the correct response by applying a rule relating the four screen positions to the response key or keys. The rule used for selecting the response varied according to choice-difficulty group assignment. The compatible and incompatible groups operated the "*Z*" key with their left middle finger, the "*X*" key with their left index finger, the "*period*" key with their right index finger, and the "*slash*" key with their right middle finger. The simple group operated the space bar with simultaneous movement of the left and right middle and index fingers. Participants were instructed to respond as quickly as possible while still maintaining accuracy. Feedback messages indicated whether the response was correct or incorrect, and if incorrect, then what the correct response key was.

The compatible group was instructed to press the left-most ("*Z*") key when the imperative stimulus appeared in the left-most position, the middle left ("*X*") key when the stimulus appeared in the middle-left position, and so on. Participants in the incompatible group were instructed to use one of four randomly assigned mappings. These mappings were constructed with three constraints. First, no position was assigned to the compatible key, as described above. Second, at least one of the two positions on either side of the fixation point had to be assigned to a key on the opposite side. Third, no simple rule, such as mirroring or flipping inside-to-outside, could relate the screen positions to the keys. Participants in the incompatible group were assigned a different mapping for each of the two sequences to reduce practice effects. Participants in the simple group responded by using the space bar regardless of the position of the stimulus.

The intertrial interval (ITI) was 1 s. Forty-eight trials were presented. The first 8 trials were practice, with 2 trials in a row in each of the four stimulus locations. These trials were not included in the data analysis.

The simple time production task. The simple time production task was preceded by 12 passive demonstration trials. The stimulus was presented in each demonstration trial in a random position for the duration of the target interval, either 3 s or 5 s. The stimulus was cleared after the interval elapsed, and the message "Get ready for next trial" was shown. Participants were instructed that the duration of the stimulus indicated the target interval and that no responses were to be made during the demonstration.

Forty-eight simple time production trials followed the demonstration, the first 8 of which were considered practice and not included in the analyses. Participants were instructed to press the space bar when the elapsed time from the imperative stimulus onset matched the target interval shown during the demonstration. Stimulus location was determined at random and was irrelevant to the task. Following every trial, feedback indicated that the response was either "too early" (if the response latency was less the 90% of the target interval), "too late" (if the response latency was greater than 110% of the target interval), or "right on time" (if the response latency was between 90% and 110% of the target interval).

For both demonstration and production trials, the ITI was 1 s when the target interval was 5 s and was 3 s when the target interval was 3 s. This ensured that the interstimulus intervals (ISIs) and total block length were equal for both target intervals.

The choice time production task. In this task, both the s-r mapping and the target interval from the preceding choice RT and simple time production blocks were relevant. Participants were instructed to choose what key to press when the stimulus appeared, based on their group and interval assignment, but to delay making the response until the end of the current target interval. For example, if a participant assigned to both the compatible group and the 3-s interval observed a stimulus that appeared in the far-left position, then he or she would ideally wait exactly 3 s after the stimulus onset before pressing the "*Z*" key. Feedback followed the first 12 trials of the task and indicated both whether the correct key was chosen (and the identity of the correct key if the wrong key was chosen) and whether the response was made too early, right on time, or too late, relative to the target interval. These practice trials were not included in the data analyses. Practice was followed by 36 test trials, 25% of which were followed by feedback. The ITI was determined on the basis of the target interval duration, as described for the simple time production task.

Analysis

The intraindividual mean, standard deviation, and *CV* of response latencies were computed for each of the two sequences of the three tasks. These variables were computed from correct responses only (where applicable) and excluded all response latencies that fell outside of 1.96 standard deviations from the mean, computed within participant, sequence, and task. Choice accuracy in the choice RT and choice time production tasks was computed for those participants in the compatible and incompatible groups.

Participants were excluded from the study if the participant's simple time production *CV* exceeded 15%. This criterion ensured that participants were sufficiently skilled at time production before attempting the more complex choice time production task. The criterion value was determined prior to data collection on the basis of pilot data. Participants were also excluded for failing to adhere to task instructions. Most commonly, this consisted of engaging in overt counting behavior during the simple time production task.

Hypotheses were tested for each variable in each task using separate analyses of variance (ANOVAs). For all of the tasks (compatibility), group was a three-level between-participants effect for the analysis of the mean, standard deviation, and *CV* of response latencies. For the analysis of choice accuracy, group had two levels because the variable was not applicable for the simple group. Duration (of the target interval) was a two-level within-participants factor in the analysis of all variables from the simple and choice time production tasks. Preliminary analyses of the choice time production data also included the order in which the target intervals were tested (3 s first or 5 s first) as a two-level between-participants effect. This tested the efficacy of counterbalancing this factor. Order of testing had no significant main effect or interactions with other effects in the model. As a result, this factor was dropped from the analyses of all tasks, as was the effect of duration (of the subsequent simple and choice time production target intervals) on the choice RT data.

Results

The critical choice time production task data are presented first in a qualitative manner. Following this are complete reports of the statistical tests, presented in the order of task administration.

Figure 1 shows the results from the choice time production task. The mean (see Figure 1A) increased with the target interval, but it did not depend on the s-r mapping. However, choice difficulty affected the *CV* (see Figure 1B) so that the incompatible group's *CV* was the largest, especially for production of the 3-s target. The compatible group's *CV* was reduced compared with the other groups. This finding is surprising given the outcome of the choice RT task in which the groups' mean and *CV* fell in the expected order from lowest to highest: simple, compatible, and incompatible.

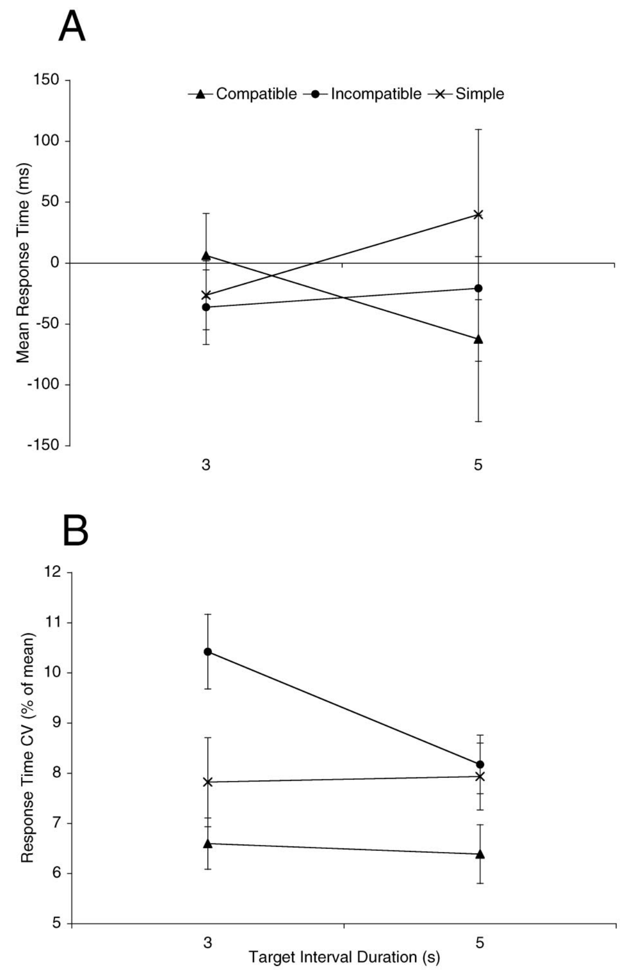

Figure 1. Experiment 1 choice time production group mean (A) intraindividual response latency means and (B) coefficients of variation (*CV*s), with standard error bars. Data are plotted as a function of target interval duration. For ease of comparison between target intervals, response latency means have been converted to mean absolute time production errors by subtracting the target interval duration.

Choice RT Task

Table 1 provides a summary of the results of the choice RT task. Group significantly affected the mean, $F(2, 33) = 107.13$, $p < .0001$, with the incompatible group being the slowest and the simple group being the fastest. Post hoc contrasts indicated that the difference between the compatible and incompatible groups' mean was significant, $F(1, 33) = 125.19$, $p < .0001$, as were the differences between the simple and incompatible groups' mean, $F(1, 33) = 189.54$, $p < .0001$, and the simple and compatible groups' mean, $F(1, 33) = 6.65$, $p < .05$.

Group significantly affected both the standard deviation, $F(2, 33) = 148.28$, $p < .0001$, and the *CV*, $F(2, 33) = 33.34$, $p < .0001$. The incompatible group's *CV* was significantly higher than those of either the compatible group, $F(1, 33) = 51.86$, $p < .0001$, or the simple group, $F(1, 33) = 48.08$, $p < .0001$. The simple and compatible groups' *CV* did not differ, $F(1, 33) = 0.07$. The incompatible group's standard deviation was significantly greater than that of either the compatible group, $F(1, 33) = 200.38$, $p < .0001$, or the simple group, $F(1, 33) = 242.47$, $p < .0001$. The simple and compatible groups' standard deviation did not differ, $F(1, 33) = 2.0$, *ns*.

The incompatible group made significantly more choice errors than did the compatible group, $F(1, 22) = 10.86$, $p < .05$. However, choice accuracy was quite high for both groups. The incompatible group's 93% accuracy equals about six errors across both task sequences.

Simple Time Production Task

Table 2 summarizes the results of the simple time production task. The duration of the target interval significantly affected the mean, $F(1, 33) = 4447.03$, $p < .0001$, but the mean was not

Table 1
Choice Reaction Time Results for All Experiments

	M		*SD*		*CV*		Accuracy	
Group	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
Experiment 1								
Compatible	409.89	12.72	63.31	4.70	15.36	0.87	98.80	0.50
Incompatible	1093.98	72.94	231.85	18.59	30.10	2.06	92.40	1.60
Simple	252.25	11.19	39.46	2.21	15.91	1.13		
Experiment 2								
Less	1109.09	62.23	409.00	44.25	36.34	2.86	79.30	2.50
More, first block	1096.16	95.28	369.35	49.45	32.98	2.96	89.20	3.40
More, fourth block	771.67	36.85	201.33	22.09	25.55	2.03	98.20	0.40
Experiment 3								
Low feedback	860.91	64.00	280.18	44.34	30.41	3.08	92.80	1.30
High feedback	948.76	65.20	297.87	28.34	30.98	1.70	91.70	2.00
Experiment 4								
Compatible	499.53	15.65	64.25	4.29	12.83	0.67	99.20	0.40
Incompatible	1093.77	56.88	402.36	39.02	36.46	2.36	90.40	2.90
Experiment 5								
Compatible	509.64	17.32	67.16	5.11	13.05	0.74	98.80	0.50
Incompatible	1039.83	87.18	338.66	41.82	32.58	3.16	89.10	3.60

Note. On the top line, the mean (*M*), standard deviation (*SD*), coefficient of variation (*CV*), and Accuracy refer to intraparticipant summary variables. On the second line, *M* and the standard error (*SE*) refer to the group means and standard errors of the intraparticipant variables. *M* and *SD* of response latency are in milliseconds. The *CV* of response latency and Accuracy of response choice are percent values.

affected by group, $F(2, 33) = 0.6$, *ns*, or by the Duration × Group interaction, $F(2, 33) = 2.18$, *ns*. Individuals' timing errors were ±2%–3% of the target interval.

Although the standard deviation was significantly larger for the 5-s target interval than for the 3-s target interval, $F(1, 33) = 55.05$, $p < .0001$, the target intervals' *CV* was not different, $F(1, 33) = 1.35$, *ns*. This result is statistical evidence for adherence to Weber's law. The grand mean *CV* was 7.9%. Group did not significantly affect either the standard deviation, $F(2, 33) = 0.03$, *ns*, or the *CV*, $F(2, 33) = 0.08$, *ns*. The Group × Target Interval interaction affected neither the standard deviation, $F(2, 33) = 0.03$, *ns*, nor the *CV*, $F(2, 33) = 0.11$, *ns*.

Table 2
Simple Time Production Results for All Experiments

		M		*SD*		*CV*	
Group	Duration	*M*	*SE*	*M*	*SE*	*M*	*SE*
Experiment 1							
Compatible	3,000	3018.54	18.64	236.17	23.96	7.81	0.78
	5,000	4978.69	58.78	378.22	44.75	7.58	0.91
Incompatible	3,000	3027.91	22.70	250.11	17.16	8.28	0.58
	5,000	4875.99	34.61	382.35	38.68	7.83	0.79
Simple	3,000	2978.89	18.78	246.38	17.20	8.26	0.57
	5,000	4967.06	57.75	378.05	32.36	7.58	0.60
Experiment 2							
Less	3,000	2992.78	19.40	281.30	24.34	9.43	0.85
More	3,000	2943.30	21.05	246.43	19.92	8.38	0.68
Experiment 3							
Low feedback	3,000	3000.63	33.54	313.00	19.69	10.38	0.56
High feedback	3,000	2973.16	26.84	283.79	21.76	9.55	0.74
Experiment 4							
Compatible	3,000	2975.88	29.71	60.20	17.38	9.21	0.64
Incompatible	3,000	3034.72	38.87	81.32	23.47	8.46	0.81
Experiment 5							
Compatible	5,000	4970.42	32.55	346.64	33.14	6.95	0.65
Incompatible	5,000	4911.40	59.31	452.78	39.46	9.23	0.81

Note. On the top line, the mean (*M*), standard deviation (*SD*), and coefficient of variation (*CV*) refer to intraparticipant summary variables. On the second line, duration (in milliseconds) is of the target interval, and *M* and *SE* refer to the group means and standard errors of the intraparticipant variables. The *M* and *SD* of response latency are in milliseconds. The *CV* of response latency is a percent value.

The absence of group effects on the mean and *CV* and the absence of duration effects on the *CV* indicate that positive effects of these factors on choice time production are not because of baseline performance differences.

Choice Time Production Task

There was a significant effect of duration on the mean, $F(1, 33) = 2880.97$, $p < .0001$, but the main effect of group, $F(2, 33) = 0.25$, *ns*, or the Duration × Group interaction, $F(2, 33) = 1.12$, *ns*, was not significant.

The standard deviation (see Table 3 for condition values) was significantly larger for the 5-s interval than for the 3-s interval, $F(1, 33) = 57.70$, $p < .0001$. In addition, the main effect of group was significant, $F(2, 33) = 4.60$, $p < .05$, such that the incompatible group had the highest and the compatible group had the lowest standard deviation. The difference between the compatible and incompatible groups was significant, $F(1, 33) = 9.18$, $p < .05$. Neither the difference between the simple and incompatible groups, $F(1, 33) = 1.90$, *ns*, nor the difference between the simple and compatible groups, $F(1, 33) = 2.72$, *ns*, was significant. The Duration × Group interaction did not significantly affect the standard deviation, $F(2, 33) = 1.28$, *ns*.

The *CV* differed significantly by group, $F(2, 33) = 5.72$, $p < .05$, with the incompatible group having the highest values and the compatible group having the lowest. The difference between the compatible and incompatible groups was significant, $F(1, 33) = 11.44$, $p < .05$. Neither the difference between the simple and incompatible groups, $F(1, 33) = 2.93$, *ns*, nor the difference between the simple and compatible groups, $F(1, 33) = 2.79$, *ns*, was significant. The Duration × Group interaction significantly affected the *CV*, $F(2, 33) = 3.65$, $p < .05$. Contrasts indicate that the Duration × Group interaction on the *CV* exists for the compatible and incompatible groups, $F(1, 33) = 4.63$, $p < .05$;, the simple and incompatible groups, $F(1, 33) = 6.20$, $p < .05$; but not the compatible and simple groups, $F(1, 33) = 0.12$, *ns*. The main effect of duration on the *CV* was nonsignificant, $F(1, 33) = 4.07$, *ns*.

The grand mean *CV* for the choice time production task was 7.9%—the same value obtained for the simple time production task. In addition, the *CV* of response latencies for the simple group was 7.9% in both tasks. This finding suggests that additional timing practice afforded by the choice time production task was not a significant factor in producing the observed results.

Choice accuracy (see Table 3 for values) was lower for the incompatible group than for the compatible group, $F(1, 22) = 12.41$, $p < .05$. This difference in choice accuracy between groups was smaller than that found in the choice RT task. The effect of duration on choice accuracy was nonsignificant, $F(1, 22) = 3.86$, *ns*. There was no effect on accuracy of the duration by mapping condition interaction, $F(1, 22) = 1.21$, *ns*.

Table 3
Choice Time Production Standard Deviation (SD) and Choice Accuracy Results for All Experiments

		SD		Choice accuracy	
Group	Duration	*M*	*SE*	*M*	*SE*
Experiment 1					
Compatible	3,000	198.44	16.75	98.80	0.40
	5,000	324.46	31.58	99.50	0.40
Incompatible	3,000	316.13	22.26	95.70	1.20
	5,000	409.53	27.90	98.10	0.60
Simple	3,000	237.44	26.93		
	5,000	395.95	36.33		
Experiment 2					
Less, Block 1	3,000	401.98	64.11	93.60	2.30
Less, Blocks 2–6		241.02	36.05	97.40	1.10
More, Block 1	3,000	254.26	30.40	98.70	0.90
More, Blocks 2–6		222.43	31.12	98.70	1.20
Experiment 3					
Low feedback, Block 1	3,000	310.05	19.62	97.40	2.00
Low feedback, Blocks 2–6		336.47	32.88	98.60	1.00
High feedback, Block 1	3,000	259.98	27.78	98.70	0.90
High feedback, Blocks 2–6		281.67	35.18	99.50	0.40
Experiment 4					
Compatible	3,000	256.43	9.74	99.00	0.40
Incompatible	3,000	324.32	16.16	97.00	0.50
Experiment 5					
Compatible	5,000	373.01	17.04	98.50	0.40
Incompatible	5,000	443.90	24.33	96.90	0.60

Note. On the top line, *SD* and Choice accuracy refer to intraparticipant summary variables. *SD* of response latency is in milliseconds. Choice accuracy is a percent value. On the second line, duration (in milliseconds) is of the target interval, and *M* and *SE* refer to the group means and standard errors of the intraparticipant variables. Block 1 and Blocks 2–6 refer to the values for the first block of trials and the mean of the second through sixth blocks, respectively.

Discussion

If response choice processing is processed in series with response timing, then the switch model predicts that the ordering of the groups' choice time production mean and *CV* should be the same as the ordering of the groups' choice RT mean and *CV*. The choice RT task produced the expected results; the incompatible group had the highest mean and *CV*, followed by the compatible and simple groups. However, choice-difficulty condition had no effect on the choice time production mean, contradicting the predictions of the switch model. In contrast, the incompatible group's *CV* was higher than the other two groups' *CV*, and the difference was larger for the 3-s interval than for the 5-s interval. This interaction of task and target interval duration indicates that the increase in timing variability was because of a nonscalar source of variability, such as the switch. However, the compatible group's *CV* was lower than the simple group's *CV*, an apparent facilitation of performance that is contrary to the model's prediction. Taken together, the choice time production data provide data both supporting and opposing the notion that response choice is processed in series with response timing.

The incompatible group's choice time production *CV* data were especially difficult to reconcile with anything but serial processing of response choice and response timing. The question, therefore, arises as to how the switch model can be extended to allow serial processing without increases in the mean. A simple way to avoid increases in the mean is to use an error correction mechanism that reduces the duration of the interval timed by the duration of choice processing. This reduction is referred to as *temporal discounting*. A formulation of this temporal discounting model is presented in the Appendix. It assumes that for a given choice-difficulty condition and target interval in the choice time production task, (a) the switch-open time mean and *CV* are equal to the choice RT mean and *CV*; and (b) the interval timed has a mean equal to the simple time production mean minus the choice RT mean, and a *CV* equal to the simple time production *CV*. Note that no assumption is made about the process by which the participant carries out temporal discounting. Use of the feedback in the choice time production task is a likely candidate, as is correction in anticipation of the demands of the choice timing task. Moreover, in practice, temporal discounting may not be perfect, as the second assumption implies. However, there is no basis for predicting partial discounting. These issues are addressed in Experiment 3.

As a test, the model was applied to individuals' outcomes and condition means were computed. The expected choice time production group means for the 3-s interval were as follows: simple = 7.9%, compatible = 7.4%, and incompatible = 11.2%. The expected choice time production group means for the 5-s interval were as follows: simple = 7.6%, compatible = 7.6%, and incompatible = 9.1%. The model predictions overestimate the compatible groups' obtained values and underestimate those for the simple group, and the predictions are slightly better for the 3-s than for the 5-s interval. The model accurately predicts that the incompatible group will have (a) higher *CV*s than the other two groups and (b) *CV*s that differ by target interval duration. Also, the model accurately predicts that the simple group will have a higher *CV* than the compatible group for production of the 3-s interval but misses the same prediction for the 5-s interval. Nonetheless, an emergent property of the temporal discounting model accounts for the compatible mapping's apparent facilitation of the *CV*, at least in part.

In order to further validate the temporal discounting model, the obtained *CV*s from the choice time production task were regressed on the expected values, computed on an individual participant basis. Separate regressions were carried out for the 3-s and 5-s target intervals so that the validity of the model can be assessed separately for conditions associated with different outcomes for the incompatible group. The model of the 3-s data was significant, $F(1, 34) = 24.88$, $p < .0001$, $r^2 = .423$, $b = 0.735$, as was the model of the 5-s data, $F(1, 34) = 18.89$, $p < .05$, $r^2 = .357$, $b = 0.561$. For the 3-s interval, the intercept term was not significant, $t(34) = 1.50$, *ns* . However, the intercept (3.2%) was significant in the case of the 5-s interval, $t(34) = 3.01$, $p < .05$.

The temporal discounting model predicted a significant, but not majority, portion of the between-participants variability in choice time production *CV*. Some of this unaccounted-for-variability may be due to limitations in the reliability of the four random variables contributing to the model. More interesting are the likely conceptual shortcomings of the model. For example, both the choice RT and simple time production variability include a motor variability component. Similarly, both tasks include stimulus anticipation and detection components. These redundancies are not treated in the temporal discounting model, as expressed as Equations 1 and 2 in the Appendix, reducing the model's accuracy. Another issue is the assumption that performance does not change across the trials of the tasks. This issue is addressed in Experiments 2 and 3.

In summary, the temporal discounting model accurately predicted the pattern of group differences and a significant portion of the individual variability in the choice time production *CV* data. Therefore, the choice time production data were consistent with the notion that response choice and response timing occur in series, provided that one accounts for error correction.

Experiment 2: Effects of Choice RT Practice on Choice Time Production

According to the temporal discounting model, the effect size of choice difficulty on choice time production depends on how long and variable the nontiming processes are but not necessarily on what processes are involved. If this is the case, then the serial hypothesis can also be tested by comparing choice time production between two groups of participants assigned to the same choice-difficulty condition but differing in response choice processing speed and reliability.

Practice is known to reduce the mean choice RT for spatially incompatible s-r mappings (Dutta & Proctor, 1992; Fitts & Seeger, 1953; Proctor & Dutta, 1993; Teichner & Krebs, 1974). It is also reasonable to expect a similar reduction in intraindividual RT variability, both in absolute and relative terms. If so, and if response choice and response timing occur in series, then choice time production should be less variable in a group that receives additional practice with the choice RT task compared with a group given less choice RT practice. In Experiment 1, the largest choice time production *CV* was observed in the incompatible group, timing the 3-s interval, so this condition is the best choice for testing the effects of choice RT practice on choice time production.

Another feature of this experiment is the increased number of trials in the choice time production task. The added trials allow for the averaging of the choice time production data into successive blocks of trials and examination of the progress of behavior during the task.

Method

Participants

Thirty-one undergraduate students at the University of Oregon served as participants. They were recruited from department of psychology courses and were rewarded with credit toward completing course requirements. Of the participants, 5 were subsequently eliminated, 3 for failing to meet performance-based inclusion requirements (see below), and 2 for failing to adhere to task instructions. Participants were randomly assigned to one of two experimental groups: "less" or "more" choice RT practice.

Apparatus

The apparatus used in this experiment was identical to that used in Experiment 1.

Stimuli

The stimuli used in this experiment were identical to those used in Experiment 1.

Procedure

Participants were tested with a single sequence of the choice RT: simple time production and choice time production tasks. The target interval was 3 s. Both experimental groups were assigned a spatially incompatible s-r mapping for the choice RT and choice time production tasks. In order to reduce one potential source of between-participants variability, all participants were assigned the same mapping. The far-left screen positions were assigned to the right-most key ("the *slash* key"), the middle-left position to the middle-right key ("the *period* key"), the middle-right position to the far-left key ("the *Z* key"), and the far-right position to the middle-left key ("the *X* key"). Participants operated the four keys with the middle and index fingers of their left and right hands.

For both experimental groups, the first 12 choice RT task trials consisted of three repetitions of each stimulus, which were excluded from the analysis. The less group was given 36 additional trials, and the more group was given 144 additional trials.

The demonstration of the target interval and the simple time production task were identical to those in Experiment 1, except eight demonstration trials were given, followed by 40 simple time production trials.

The choice time production task was similar to that of Experiment 1, but with more trials. Feedback was given after the first eight trials, and these trials were excluded from the analysis. After a short break, participants were given 72 trials. Feedback was given on 25% of these trials.

Analysis

The more group's choice RT data were subdivided into four blocks of 36 trials, and averages were computed separately for each block. For the less group, all 36 trials of the choice RT task were aggregated into a single block. For both groups, the 72 trials of the choice time production task were subdivided into six blocks of 12 trials, and averages were computed separately for each block. All other aspects of the averaging were identical to that of Experiment 1, including criterion for excluding trials and participants and exclusion of incorrect responses from calculation of the mean, standard deviation, and *CV* of response latencies.

The choice RT variables for practice group (a between-participants effect) differences between the first (and only) block of trials for the less group and the fourth block of trials from the more group were tested using ANOVAs. Separate ANOVAs were carried out for choice accuracy, the mean, standard deviation, and *CV* of response latencies.

Analysis of data from the simple time production task included the same model but did not include tests of choice accuracy.

Analysis on the choice time production data resulted in two factors entered into separate ANOVAs on each of the four variables. Practice group was entered as a between-participants effect, and block was entered as a within-participants effect. Reported probability values for the main effect of block and the Group × Block interaction were corrected using the Huynh-Feldt epsilon.

Two planned contrasts were chosen on the assumption that if temporal discounting were occurring, then it must be occurring early in the task, or else group effects on the mean would have been observed in Experiment 1. The first contrast was the simple contrast between groups within the first block. To be as conservative as possible, the error term for this contrast was the effect of participants nested within groups, reflecting the fact that Blocks 2–6 did not contribute to the contrast variance. The second contrast was the first-order Helmert contrast crossed with group, or the group difference in change between the first blocks' mean and the mean of the subsequent levels. The error term for this contrast was Subject (Group) × Block. The contrasts on the choice accuracy, standard deviation, and *CV* measures are reported as one-tailed *t* values, with an alpha threshold of 0.05 in light of the positive effects of group on those variables in Experiment 1. The questions raised by the contrasts were (a) Is the less group less accurate in choice and more variable in latency at the start of the choice time production task? and (b) does the less group show a greater rate of performance improvement following the first block of trials?

Results

Figure 2 shows the choice time production mean (see Figure 2A) and *CV* (see Figure 2B) results.

The results for the mean and *CV* followed the same pattern. For both groups, performance improved significantly across the choice time production task. For both measures, the less group's performance was worse than that of the more group in the first block. There was a marginal difference in the rate of decrease of the groups' mean but a significant difference in the rate of improvement of the *CV*.

Choice RT Task

The results for all variables are summarized in Table 1. Comparing the more group's fourth block with the less group's first (and only) block, the more group had a significantly smaller mean, $F(1, 24) = 21.77$, $p < .0001$; standard deviation, $F(1, 24) = 17.63$, $p < .01$; and *CV*, $F(1, 24) = 9.48$, $p < .05$. Response choice accuracy was also significantly better for the more group, $F(1, 24) = 55.69$, $p < .0001$.

Simple Time Production Task

The results for all variables are summarized in Table 2. The effect of group was not significant for the mean, $F(1, 24) = 2.99$, *ns*; standard deviation, $F(1, 24) = 1.23$, *ns*; and the *CV*, $F(1, 24) = 0.92$, *ns*. The grand mean *CV* was 8.9%.

Choice Time Production Task

The mean shortened significantly over the course of the six blocks, $F(5, 120) = 2.35$, $p < .05$. The mean was not affected by

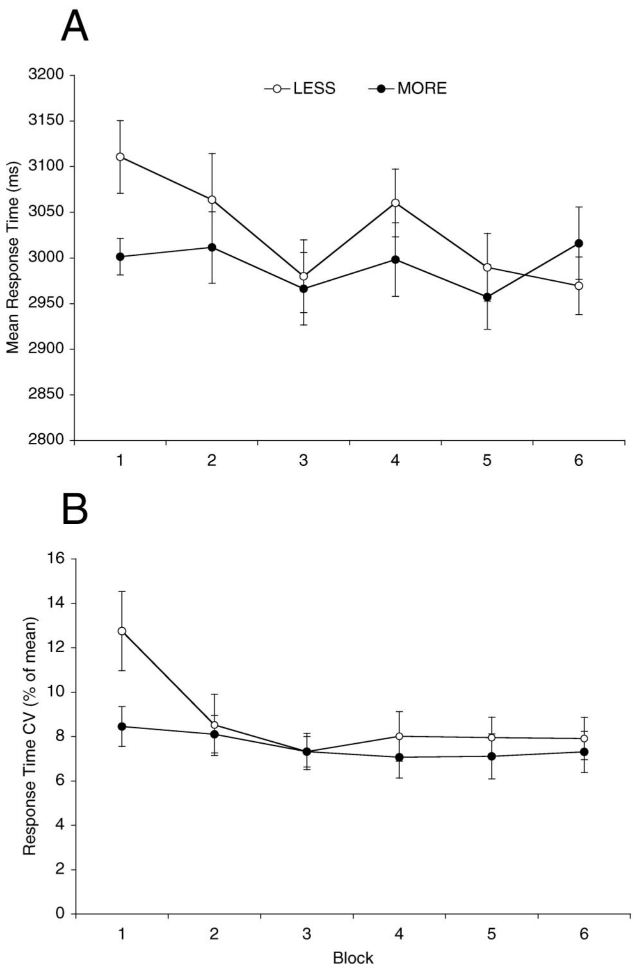

Figure 2. Experiment 2 choice time production group mean (A) intraindividual response latency means and (B) coefficients of variation (*CV*s), with standard error bars. Data are plotted as a function of testing block within the choice time production task.

group, $F(1, 24) = 0.76$, *ns*, nor by the Block × Group interaction, $F(5, 120) = 1.28$, *ns*. However, the groups' mean differed significantly in the first block, $t(24) = 2.21$, $p < .05$. The first Helmert contrast within the Block × Group interaction was nonsignificant, $t(120) = 1.71$, *ns*.

Both the *CV*, $F(5, 120) = 4.54$, $p < .05$, and standard deviation (see Table 3 for values), $F(5, 120) = 5.13$, $p < .05$, significantly decreased over the six testing blocks. There was no main effect of group on either the *CV*, $F(1, 24) = 0.86$, *ns*, or the standard deviation, $F(1, 24) = 0.96$, *ns*. The Block × Group interaction did not affect the *CV*, $F(5, 120) = 1.79$, *ns*; nor the standard deviation, $F(5, 120) = 2.19$, *ns*. However, the less group's *CV* was significantly greater than the more group's in the first block, $t(24) = 1.94$, $p < .05$, one-tailed. Similarly, the less group's standard deviation was significantly greater than the more group's in the first block, $t(24) = 2.08$, $p < .05$, one-tailed. The decrease in *CV* following the first block was significantly greater for the less group than for the more group, $t(120) = 2.91$, $p < .05$, one-tailed. This effect was also significant for the standard deviation, $t(120) = 3.22$, $p < .05$, one-tailed. The grand mean of the *CV* was 8.16%.

Choice accuracy (see Table 3 for values) differed nonsignificantly between groups, $F(1, 24) = 3.57$, $p < .1$. Accuracy did not differ as a function of block, $F(5, 120) = 1.32$, *ns*, or of the Block × Group interaction, $F(5, 120) = 1.21$, *ns*. In the first block, the group difference was significant, $t(24) = 2.05$, $p < .05$, one-tailed. Choice accuracy increased more for the less group than for the more group between the first and subsequent blocks, $t(120) = 1.96$, $p < .05$, one-tailed.

Discussion

If the serial processing hypothesis and the temporal discounting model are correct, then choice time production performance can change if response choice processing speed and variability change, even when the choice-difficulty condition does not change. The practice manipulation facilitated this comparison by producing two groups that differed in the speed and reliability of their response choice decisions, as indicated by the choice RT data, while performing identical tasks. The less group ended the choice RT task, with RT measures comparable to those from the incompatible group in Experiment 1. In contrast, the more group ended the choice RT task with a substantially lower mean, standard deviation, and *CV*.

The additional choice RT practice improved choice time production performance at the beginning of the task. In the first block, the more group's responses were faster and less variable, and choice accuracy was improved, compared with the less group. This supports the serial processing hypothesis because the ordering of the groups' mean and *CV* was the same in the choice RT and choice time production tasks. This finding also supports the temporal discounting model's assumption that adding an attention-demanding processing stage (such as response selection) to a time production task is insufficient to determine whether choice time production will be adversely affected. Rather, it is the dynamics of those nontiming processes that determine the degree to which interference between timing and nontiming processes can be measured in this choice-timing task.

This experiment also showed the change in choice time production as the task progressed. For the less group, all four dependent variables rapidly converged to the more group's level following the first block of trials. This convergence included the mean, an effect anticipated by the standard switch model. These changes were likely because of participants' use of feedback both to improve response choice processing to reduce variability and to implement temporal discounting to reduce the mean. However, early in the choice time production task, the less group's mean was longer than the target interval but shorter than the sum of the target interval and the choice RT mean (the maximum mean predicted by the switch model without temporal discounting). This finding indicates that temporal discounting occurs either rapidly following the feedback in the eight practice trials or before the choice time production task, or perhaps both. This issue is addressed in Experiment 3.

Forward application of the temporal discounting model yielded the following predictions of the groups' mean *CV* in the first block of the choice time production task: more = 9.5%, less = 15.3%. The more group's estimated *CV* exceeded the obtained value by 0.85%, whereas the less group's estimated *CV* exceeded the obtained value by 2.45%. The overestimation of the groups' *CV* may reflect an improvement in response choice processing dynamics in the choice time production task relative to the choice RT task. This assertion is supported by the finding that the response choice accuracy was substantially improved at the start of the choice time production task relative to the choice RT task as well as by the fact that the overestimation was greater for the less group, which has the most room for improvement.

The regression model comparing the individuals' obtained *CV* values with the expected values from the temporal discounting model was significant, $F(1, 24) = 11.45$, $p < .05$, $r^2 = .323$, $b = 0.713$. In addition, the intercept was not significantly different from zero, $t(24) = 0.68$, *ns*. These parameter estimates compare favorably with the model of the data from the 3-s target interval conditions in Experiment 1. The relatively large proportion of variance accounted for is especially promising given that the obtained *CV* values in this experiment were computed from one third fewer trials and were therefore likely to be less reliable than the equivalent measurements from Experiment 1.

The success of the RT practice manipulation and the forward application of the temporal discounting model together supported the hypothesis that response choice and response timing occur in series and provided good converging evidence of the validity of the temporal discounting model.

Experiment 3: Choice Time Production With and Without Feedback

Dual-task studies of time production and attention typically omit feedback from the test conditions (e.g., Fortin & Breton, 1995; Fortin et al., 1993). The purpose of omitting the feedback is to prevent the relearning of the target interval under the changed conditions, thereby reducing changes to the dual-task time production mean. Experiments 1 and 2 included some choice time production feedback in order to reduce random trial-to-trial variability that may have interfered with the ability to detect the effects of the choice difficulty manipulations on the *CV*. This strategy was apparently successful to the extent that the *CV* data provided evidence consistent with serial processing of the response choice and timing components of the tasks.

However, two questions remain. First, can serial processing be demonstrated in the choice time production task in the absence of feedback? If so, one may expect the incompatible choice time production mean to be longer than the target interval. Second, by what means was temporal discounting carried out? The results of Experiment 2 suggested that in addition to the adjustments made during the choice time production task, with the assistance of the feedback, some adjustment may occur very early in the task or prior to it. These hypotheses were tested in this experiment by comparing two groups of participants who performed choice time production of a 3-s interval with an incompatible s-r mapping, with and without feedback.

Formal application of the temporal discounting model was omitted because the two groups performed the same choice RT task. The model is therefore incapable of predicting positive effects of a manipulation applied to the choice time production task.

Method

Participants

Twenty-nine individuals recruited from the Columbia University community were paid $20 each to participate in this experiment. Two participants were subsequently eliminated from the analysis because of failure to adhere to task instructions. One participant was eliminated because of failure to meet performance-based inclusion requirements. Participants were randomly assigned to one of two experimental groups: "high" or "low" choice time production feedback.

Apparatus

This experiment was conducted using a Macintosh iBook computer, running PsyScope Version 1.2.5. The USB keyboard provides 2-ms timing accuracy. The 12.1 in. (30.7 cm) liquid crystal display screen provided a slightly smaller viewable area than the system used in the previous experiments.

Stimuli

The stimuli used in this experiment were similar to those used in Experiment 1 but were about 5% smaller because of the smaller screen size.

Procedure

The procedure used for both the high and low groups was similar to that of the less group in Experiment 2 in terms of the number of trials and blocks for the single run through all three tasks, the amount of feedback and practice trials for the choice RT and simple time production tasks, the use of a 10% criterion for timing feedback, the use of a 3-s target interval, and the spatially incompatible s-r mapping used in the choice RT and choice time production tasks.

The choice time production task began with eight practice trials that were excluded from the analysis. For the high group, the first two of these trials were followed by feedback. The high group also received feedback following 25% of subsequent choice time production trials. The low group received no feedback at all following either the practice or test choice time production trials.

Analysis

The simple and choice time production tasks were analyzed using the methods described for Experiment 2, including participant exclusion criterion, variables, and ANOVA models and planned contrasts. The methods described for Experiment 2 were used for the choice RT task analysis, but comparisons were between the first (and only) blocks of trials.

Results

The Experiment 3 choice RT mean (see Figure 3A) and *CV* (see Figure 3B) by block for both groups are illustrated in Figure 3.

Averaged over the six blocks, the low group's choice time production mean was 410 ms longer than that of the high group. However, the *CV* was unaffected.

Choice RT Task

The results for all variables are summarized in Table 1. The effect of group was not significant for the mean, $F(1, 24) = 0.92$, *ns*; standard deviation, $F(1, 24) = 0.11$, *ns*; *CV*, $F(1, 24) = 0.03$, *ns*; or choice accuracy, $F(1, 24) = 0.21$, *ns*.

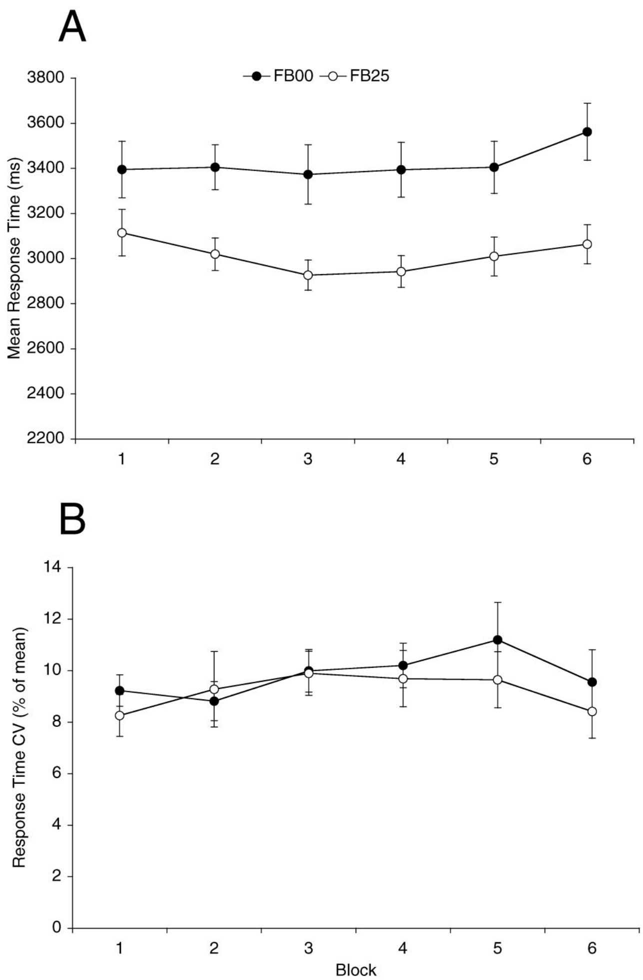

Figure 3. Experiment 3 choice time production group mean (A) intraindividual response latency means and (B) coefficients of variation (*CV*s), with standard error bars. Data are plotted as a function of testing block within the choice time production task. FB00 = 0% feedback; FB25 = 25% feedback.

Simple Time Production Task

The results for all variables are summarized in Table 2. The difference between groups was not significant for the mean, $F(1, 24) = 0.41$, *ns*; standard deviation, $F(1, 24) = 0.99$, *ns*; or *CV*, $F(1, 24) = 0.81$, *ns*. The grand mean *CV* was 9.96%.

Choice Time Production Task

The low group's mean was significantly longer than that of the high group, $F(1, 24) = 12.40$, $p < .05$. The mean was affected neither by block, $F(5, 120) = 1.53$, *ns*, nor by the Block × Group interaction, $F(5, 120) = 0.62$, *ns*. The difference in the groups' mean was nonsignificant in the first block, $t(24) = 1.73$, *ns*. The interaction between the group effect and the contrast between the first and subsequent blocks were not significant, $t(120) = 1.48$, *ns*.

Neither the *CV*, $F(1, 24) = 0.37$, *ns*, nor the standard deviation (see Table 3 for values), $F(1, 24) = 2.60$, *ns*, differed between groups overall. The main effect of block was not significant for both the *CV*, $F(5, 120) = 1.37$, *ns,* and standard deviation, $F(5, 120) = 1.13$, *ns*. The general Block × Group interaction affected neither the *CV*, $F(5, 120) = 0.41$, *ns*, nor the standard deviation, $F(5, 120) = 0.26$, *ns*. The interaction of group and the contrast between the first and subsequent blocks were not significant for either the *CV*, $t(24) = 0.32$, *ns*, or the standard deviation, $t(24) = 0.10$, *ns*. The groups' *CV* did not differ in the first block, $t(24) = 0.95$, *ns*, nor was there a significant difference in the groups' standard deviation, $t(24) = 1.45$, *ns*, one-tailed. The grand mean of the *CV* was 9.51%.

For choice accuracy (see Table 3 for values), there was no main effect of group, $F(1, 24) = 1.15$, *ns*; block, $F(5, 120) = 0.65$, *ns*; or the Block × Group interaction, $F(5, 120) = 1.09$, *ns*. Choice accuracy did not differ by group in the first block, $t(24) = 0.59$, *ns*, nor as a function of the interaction of group and the contrast between the first and subsequent blocks, $t(120) = 0.24$, *ns*.

Discussion

The effectiveness of the choice time production feedback was apparent in the significant difference between the groups' mean. The high group's data were similar to the less group's data in Experiment 2, showing a decline in the mean from 3,114 ms in the first block to an average of 2,992 ms in the other five blocks. In the absence of feedback, the low group's choice time production mean was substantially longer than the 3-s target interval. This result was an important demonstration of serial processing of response timing and choice, more similar to those typically reported than are increases in variability and violations of the scalar property. Moreover, the low group's mean did not approach that which would be expected on the basis of the assumption of pure serial processing of the choice and timing aspects of the task in the absence of temporal discounting. That is, the low group's choice time production mean of 3,422 ms was 439 ms less than the sum of the low group's choice RT mean and the target interval, or 3,861 ms. This discrepancy cannot be explained by rapid adjustment to the very early feedback trials because the practice trials did not include feedback. Thus, these data suggest that there is some other mechanism behind temporal discounting in addition to the effects of the feedback.

That the low group's mean began short of the strict serial prediction and changed little over the course of the first few blocks suggests that this additional mechanism of temporal discounting acted prior to the start of the task. That is, participants may have shortened their temporal criteria in advance of the increased demands of the choice time production task (compared with the simple time production task). "Executive" temporal discounting of this type was feasible given that task instructions fully inform participants about all three tasks before beginning the experiment.

An alternative hypothesis is that the low group's 422-ms overestimate of the 3-s target interval approximates the total duration of nontemporal processing during the choice time production task. In order for this to be the case, one would have to be able to account for the Group × Duration interaction on the incompatible group's *CV* in Experiment 1 using this value. Applying the temporal discounting model to a hypothetical situation can test this possibility. Assuming that choice time production of 3- and 5-s intervals was accurate (as in Experiment 1), the duration of nontemporal processing was 422 ms, and the *CV* of the RT was

30.41% (the low group's choice RT *CV*, see Table 1); the predicted *CV* for the 3-s interval would be 9.9%, and the predicted *CV* for the 5-s interval would be 9.85%. The presence of the scalar property suggests that 422 ms is an underestimate of duration of nontemporal processing.

The *CV* did not differ between groups. This result indicates that the low group's response latency variability increased in proportion to the increase in the group's mean. Scalar variability of this type is the hallmark of the operation of the internal clock, suggesting that the increase in the mean was due to an increase in the duration of the operation of the internal clock rather than to response choice processes. This fact is consistent with the principles of the temporal discounting model, which suggests that the result of error correction is a reduction in the duration of the interval timed by the internal clock.

Another point about the *CV* data is that they were lower than either the incompatible group's *CV* (for the 3-s target) in Experiment 1 or the less group's *CV* in Experiment 2. This effect is almost certainly because of the fact that out of the five experiments reported here, the two groups in this experiment had the fastest incompatible s-r choice RT.

In summary, omitting feedback from the choice RT task produced increased mean data that were consistent with the notion that response choice and timing processes occur in series. The data also indicated that error correction was likely used in temporal discounting in Experiments 1 and 2 both before the task and during the task using feedback.

Experiments 4 and 5: Effects of Stimulus Onset Asynchrony (SOA) on Choice Time Production With Two Cues

In addition to the omission of feedback, the choice time production task of Experiment 1 differed from some important experimental precedents (e.g., Fortin & Breton, 1995; Fortin et al., 1993) in the use of an integrated timing and response-choice signals. The next two experiments explored the effects of the delay between the onset of separate timing and response choice signals on choice time production in groups that differed in response choice difficulty. In general, serial processing of response choice and timing should have been unaffected by this manipulation, so the choice time production *CV* should have differed between the groups at all values of the delay. An interaction between group and the delay may imply that the mechanisms that mediate the relation between timing and attention before and after an interruption in the timing signal are not independent.

Experiments 4 and 5 differ only in the duration of the target interval. Experiment 5 was conducted to address an issue that arose from the results of Experiment 4.

As in Experiment 3, application of the formal temporal discounting model was omitted because the experimental manipulation was not applied to the choice RT task. As a result, the model cannot predict positive effects of the manipulation applied during the choice time production task.

Method

Participants

Undergraduate students at the University of Oregon served as participants in Experiment 4. Thirty-one were recruited from department of psychology courses and were rewarded with credit toward completing course requirements. Of the participants, 7 were subsequently eliminated, 4 failed to meet performance-based inclusion requirements (see below), and 3 failed to adhere to task instructions.

Twenty-eight Columbia University undergraduates served as participants in Experiment 5. Two participants were removed from the analysis for failing to meet performance-based inclusion requirements.

In both experiments, participants were randomly assigned to one of two experimental choice difficulty groups: "compatible" or "incompatible."

Apparatus

The computer apparatus used in these experiments was identical to that used in Experiment 1. Experiment 4 was conducted at the University of Oregon, and Experiment 5 was conducted at Columbia University.

Procedure

The tasks and procedure for Experiments 4 and 5 were identical, except where noted.

Participants were run once through the three tasks. The choice RT task was identical to that used in Experiment 1.

The target duration for the simple time production task and the choice time production task was 3 s in Experiment 4 and 5 s in Experiment 5. The simple time production task was similar to that used in Experiment 1, but the timing signal was presented centrally and consisted of an exclamation point that replaced the cross-shaped fixation point 500 ms after the appearance of the warning signal array. The simple time production task consisted of 40 trials, of which the first 4 were excluded from analysis.

Two signals were used in this choice time production task, one to start timing and one to signal the identity of the response. The timing signal was presented at fixation, replacing the cross-shaped fixation point that appeared with the warning signal array. This signal could appear 250, 500, or 750 ms after onset of the warning signal array. The discriminative stimulus was a large "*X*" presented for 100 ms in one of the four positions, marked by the underscore characters of the warning signal array. This stimulus appeared after an interval of 0, 0.1, 0.5, or 1.5 s. This interval is referred to as the *SOA*. Like previous versions of this task, participants were required to make a single response after the target interval had elapsed and after correctly determining the identity of the response on the basis of the stimulus location and group assignment. The incompatible mapping was the same one used in Experiment 2.

Two hundred thirty-six trials were presented during the choice time production task. The first 12 trials were practice and cycled through each of the four stimulus positions. Feedback was presented after each of these trials. All 12 of these trials were eliminated from the analysis. The rest of the trials were presented in blocks of 28 trials. A break was provided between practice and the beginning of testing as well as between testing blocks. The first 4 trials of each block were each followed by feedback identical to that described in Experiment 1 and were excluded from analysis. Following these 4 feedback trials, 24 trials were given without any additional feedback. These 24 trials consisted of 6 trials with each of the 4 SOA values. Across each pair of successive blocks, the 12 trials presented in each of the 4 SOA values also were presented three times in each of the four stimulus positions. That is, four complete crossings of the four stimulus positions and 4 SOA values were presented in each successive group of 48 trials that were presented without feedback.

Analysis

Separate analyses were conducted for Experiments 4 and 5. These analyses were identical, except where noted.

Averaging, exclusion of trials, calculation of variables, and performance-based exclusion of participants were carried out in a manner identical to that in Experiment 1.

Group, a between-participants effect, was used in the ANOVAs of the choice RT and the simple time production task data as the sole source of variance in the model. Analysis of the choice time production task included SOA as an additional within-participants effect with four levels. Data from the eight blocks of trials in the choice time production task were aggregated in order to obtain enough trials ($n = 48$) in each SOA condition to ensure adequate sampling.

The use of the difference between the 0-s SOA condition and the mean of the other three SOA conditions as a planned contrast reflects the fact that the 0-s SOA condition was a replication of the choice time production conditions of Experiment 1. However, no prediction about the direction of this effect was made, and so the probabilities are reported as two-tailed *t* tests. Furthermore, in order to directly replicate the findings in Experiment 1 regarding group differences when timing a 3-s interval, one-tailed *t* tests were used to contrast the groups' *CV*, standard deviation, and choice accuracy within the 0-s SOA condition in Experiment 4. For completeness, the same contrasts were used on the mean in Experiment 4 and all variables in Experiment 5, but these tests are reported with respect to the two-tailed *t* distribution.

Results of Experiment 4

The data from the choice time production task are illustrated in Figure 4. Figure 4A shows that the mean increased as the SOA increased. Also, the SOA interacted with group so that there was a small group difference in the mean when the SOA was 0 or 0.1 s, but when the SOA was 0.5 or 1.5 s, the mean of the incompatible group was longer than the mean of the compatible group.

In Experiment 1, the incompatible group's choice time production *CV* was significantly greater than the compatible group's *CV* when the target interval was 3 s. Figure 4B shows a similar phenomenon when the SOA was 0 s. In general, timing variability was greater for the incompatible group across values of the SOA. Moreover, the difference between the groups was larger for the 0-s SOA than for any of the three nonzero SOA values.

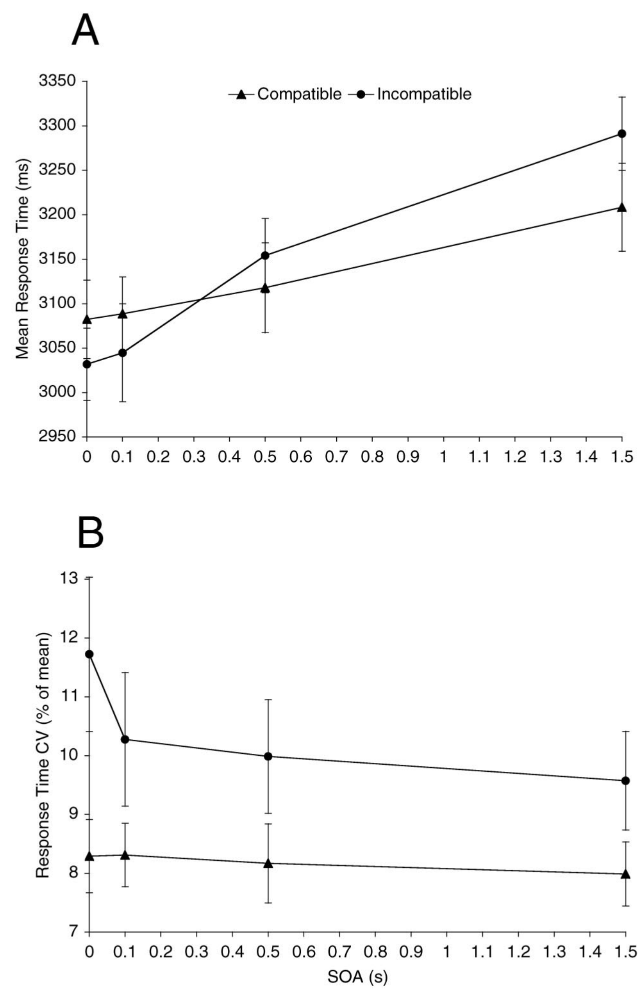

Figure 4. Experiment 4 choice time production group mean (A) intraindividual response latency means and (B) coefficients of variation (*CV*s), with standard error bars. Data are plotted as a function of stimulus onset asynchrony (SOA).

Choice RT Task

The choice RT variables are summarized in Table 1. Responses were significantly slower for the incompatible group than for the compatible group, $F(1, 22) = 101.48$, $p < .0001$. Response latencies of the compatible group were significantly more consistent than those of the incompatible group, as measured by both the standard deviation of response latencies, $F(1, 22) = 74.19$, $p < .0001$, and the *CV*, $F(1, 22) = 92.35$, $p < .0001$. Choice accuracy was significantly lower for the incompatible group than for the compatible group, $F(1, 22) = 9.07$, $p < .01$.

Simple Time Production Task

The simple time production variables are summarized in Table 2. No significant between-groups differences emerged in the mean, $F(1, 22) = 1.45$, *ns*; the standard deviation, $F(1, 22) = 0.33$, *ns*; or the *CV*, $F(1, 22) = 0.53$, *ns*. The grand mean *CV* was 8.8%, a value close to that obtained in Experiment 2.

Choice Time Production Task

As in Experiment 1, group did not have a significant effect on the mean, $F(1, 22) = 0.01$, *ns*. However, the SOA did have a significant effect on the mean, $F(3, 66) = 38.92$, $p < .0001$, equivalent to an increase of 0.122 ms per millisecond of SOA. The contrast of the 0-s SOA to the other three levels of that effect was also significant, $F(1, 66) = 32.44$, $p < .0001$, reflecting the large linear trend across these values. The mean was also significantly affected by the Compatibility Group × SOA interaction, $F(3, 66) = 5.12$, $p < .05$. This result reflects a difference between the compatible group's slope of 0.084 ms per millisecond of SOA and the incompatible group's slope of 0.1734 ms per millisecond of SOA.

The compatible group's standard deviation (see Table 3 for values) was nonsignificant compared with that of the incompatible group, $F(1, 22) = 3.47$, *ns*. Similarly, the compatible group's *CV* was nonsignificant compared with that of the incompatible group, $F(1, 22) = 3.60$, *ns*. The main effect of SOA did not significantly affect the standard deviation, $F(3, 66) = 1.66$, *ns*, but it did affect the *CV*, $F(3, 66) = 4.72$, $p < .01$. However, the contrast between the 0-s SOA and the mean of the other three SOA values was significant for both the standard deviation, $F(1, 66) = 4.88$, $p < .05$, and the *CV*, $F(1, 66) = 11.88$, $p < .05$.

The Compatibility Group × SOA interaction did not significantly affect the standard deviation, $F(3, 66) = 1.90$, *ns*, but it did significantly affect the *CV*, $F(3, 66) = 3.03$, $p < .05$. The interaction of compatibility group and the difference between the 0-s SOA and the mean of the other SOA values was significant for both the standard deviation, $F(1, 66) = 5.57$, $p < .05$, and *CV*, $F(1, 66) = 8.78$, $p < .05$. Considering only the 0-s SOA condition, there were significant effects of group on the standard deviation, $t(22) = 2.30$, $p < .05$, one-tailed, and the *CV*, $t(22) = 2.36$, $p < .05$, one-tailed.

Choice accuracy (see Table 3 for values) was better for the compatible than for the incompatible group, $F(1, 22) = 6.57$, $p < .05$. The SOA did not significantly affect choice accuracy, $F(3, 66) = 1.03$, *ns*, nor did the Compatibility Group × SOA interaction, $F(3, 66) = 2.04$, *ns*. Choice accuracy did not differ between the 0-s SOA and the other conditions, $F(1, 66) = 0.72$, *ns*. The interaction between group and the contrast between the 0-s SOA and the other values was not significant, $F(1, 66) = 0.45$, *ns*.

Results of Experiment 5

Figure 5A shows that the choice time production task mean increased as the SOA increased, but the effect of the SOA on the two groups was approximately equal. The small overall difference between the groups was not reliable.

Figure 5B shows the choice time production *CV* data. In general, timing variability was marginally greater for the incompatible group across values of the SOA. However, this effect most likely reflected the fact that for the first time in this series of experiments, the two groups differed significantly in their baseline simple time production *CV* data. Of most interest, there was not any significant difference between the zero- and nonzero-SOA conditions, as in Experiment 4.

Choice RT Task

The choice RT variables are summarized in Table 1. The incompatible group had a slower mean, $F(1, 24) = 35.58$, $p < .0001$; greater *CV*s, $F(1, 24) = 36.12$, $p < .0001$; a greater standard deviation, $F(1, 24) = 41.53$, $p < .0001$; and lower choice accuracy, $F(1, 24) = 7.28$, $p < .05$, compared with the compatible group.

Simple Tme Production Task

The simple time production results are summarized in Table 2. The two groups did not reliably differ in the mean, $F(1, 24) = 0.76$, *ns*. However, unlike previous experiments, the incompatible group had a nonsignificant standard deviation, $F(1, 24) = 4.24$, $p < .1$, and a reliably greater *CV*, $F(1, 24) = 4.84$, $p < .05$. Because the groups ran through identical tasks, these were almost certainly false positive results.

Choice Time Production Task

Group had no reliable effect on the mean, $F(1, 24) = 0.61$, *ns*, but the mean increased reliably with the SOA, $F(3, 72) = 17.11$, $p < .05$. Unlike Experiment 4, the SOA × Group interaction did not reliably affect the mean, $F(3, 72) = 0.34$, *ns*.

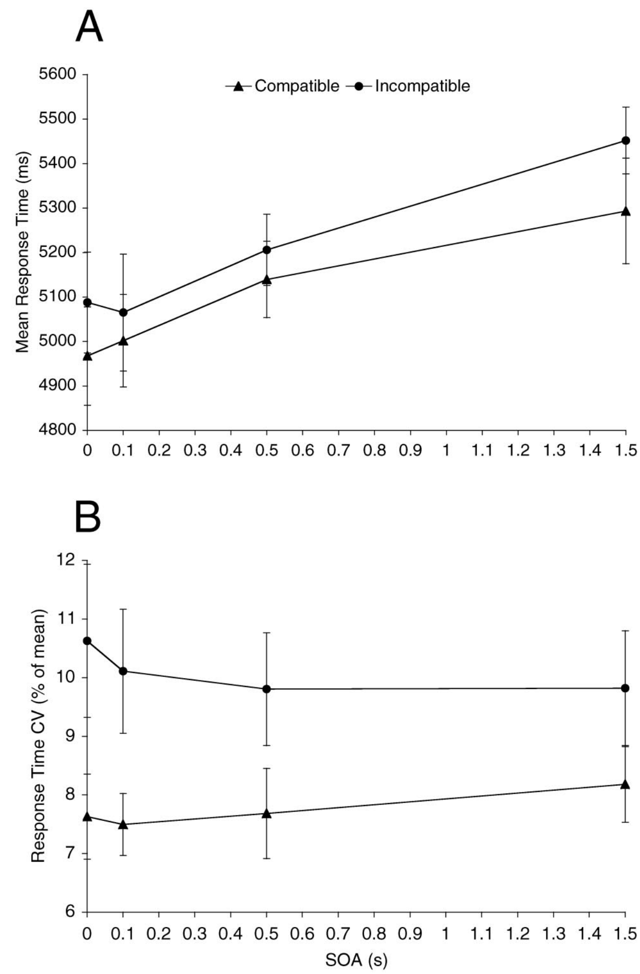

Figure 5. Experiment 5 choice time production group mean (A) intraindividual response latency means and (B) coefficients of variation (*CV*s), with standard error bars. Data are plotted as a function of stimulus onset asynchrony (SOA).

Group had a significant effect on the standard deviation (see Table 3 for values), $F(1, 24) = 4.77$, $p < .05$, and a nonsignificant effect on the *CV*, $F(1, 24) = 3.92$, $p < .1$. These differences likely reflect similar differences between the groups found in the simple time production task. Unlike Experiment 4, the *CV* was not affected by either the main effect of SOA, $F(3, 72) = 0.42$, *ns*, or the SOA × Group interaction, $F(3, 72) = 1.15$, *ns*. A similar pattern was found for the effect of SOA, $F(3, 72) = 2.30$, *ns*, and the SOA × Group interaction, $F(3, 72) = 0.72$, *ns*, on the standard deviation.

Choice accuracy (see Table 3 for values) did not differ significantly by group, $F(1, 24) = 3.18$, *ns*, or by SOA, $F(3, 72) = 2.37$, $p = .08$. The SOA × Group interaction was not significant, $F(3, 72) = 2.37$, *ns*.

Discussion

In Experiments 4 and 5, the significant main effect of SOA on the mean was linearly related to the SOA value. An explanation of this effect may be forthcoming from studies of the "gap" procedure (Fortin, 2003; Fortin & Masse, 2000). In that procedure, the timing signal is interrupted, but no additional cognitive processing is required during the interruption. It was found that the produced intervals lengthened as the interval between the onset of the timing signal and the onset of the gap increased. The proposed explanation for this effect was that the switch between the pacemaker and the accumulator was opening briefly and periodically in anticipation of an interruption in the timing signal, resulting in relatively slowed temporal accumulation during the pregap period that was proportional to the SOA. The main effect of the SOA on the mean reported here is consistent with this hypothesis.

However, this hypothesis does not predict the interaction between the effect of choice difficulty and the effect of SOA on the mean observed in Experiment 4. This interaction is of theoretical significance because it may reflect an interaction of attention mechanisms acting before and after the appearance of the choice stimulus. For example, anticipation of the choice stimulus could alter the duration or variability of choice processing following its onset. An alternative is that the interaction reflects interference between choice and timing close to the execution of the response. Because choice processing is longer for the incompatible group than for the compatible group, choice processing may continue past the desired termination of the target interval more frequently for the incompatible group following the longer SOA values. This group difference would be reduced as the SOA is reduced because the frequency for disruptively long choice processing approaches zero for both groups as the SOA approaches zero. In order to test this hypothesis, the conditions of Experiment 4 were repeated in Experiment 5, but with a longer target interval. The results of Experiment 5 support this hypothesis because the SOA × Group interaction was not observed.

The absence of main effects of group on the mean in Experiments 4 and 5 also suggests that the feedback was sufficient to allow for temporal discounting of the effect of choice difficulty but not of the effect of the anticipation of interruption. This effect is discussed further in the General Discussion section.

There were two notable findings in the *CV* data. First, the difference between the choice difficulty groups in the 0-ms SOA condition of Experiment 4 was an important replication of the central finding of Experiment 1. This finding is notable both because of its size, which was approximately the same size as that found in Experiment 1, and because it generalizes the effect to the conditions of Experiment 4. Second, this group difference in *CV* was marginal across all values of SOA, contrary to what one might expect on the basis of the temporal discounting model.

Two factors contributed to the marginal group effect on the *CV* in Experiment 4. First, the compatible group's *CV* at all values of SOA and the incompatible group's *CV* in the nonzero-SOA conditions were all about 1.5% greater than the compatible group's *CV* for the 3-s target in Experiment 1. These results suggest that the SOA itself was contributing to timing variability. Further evidence for this is a similar elevation in the compatible group's *CV* in Experiment 5. Likely sources of this variability include inconsistency, in which cue participants attend to first, as well as the need to shift attention between the central timing cue and the peripheral choice cue. Second, the incompatible group's *CV* was smaller in the nonzero-SOA condition compared with the 0-ms SOA conditions, as indicated by the significant planned contrast within the Group × SOA interaction. One possible explanation is that for the incompatible group, the feedback was increasingly effective at the longest SOA values, as choice processing was increasingly more likely to extend beyond the target interval and perhaps the feedback threshold. This mechanism, similar to the one proposed for the mean effect, would reduce the variability for the longer SOA values. As with the mean effect, the absence of a Group × SOA interaction in Experiment 5 seems to support this hypothesis.

In summary, the main effect of SOA on the mean in both Experiments 4 and 5 support the notion that attention affects timing before an interruption in the timing signal. Like the choice difficulty and practice effects in Experiments 1 and 2, the anticipatory attention effects may be mediated by the internal clock's switch. The finding of marginal group effects on the *CV* in Experiment 4 was contrary to the predictions of the temporal discounting model. This finding seems to stem from technical aspects related to the use of two signals and long SOA values rather than to the absence of serial processing of timing and choice, or to an interaction of attention processes acting before and after the interruption. This issue will have to be resolved with additional experiments.

General Discussion

Experiments 1 and 2 provided data in support of serial response choice and response timing processing to the extent that the groups with the highest choice RT *CV* had the highest choice time production *CV*. The associated violation of the scalar property (see Experiment 1) suggested that this increase in *CV* stemmed from added nonscalar variability because of the effect of attention on the internal clock's switch. Problematic for the serial theory were the lack of effects of choice difficulty on the mean and the compatible group's low *CV*. Both of these phenomena were explained by including an unspecified error correction process in the standard switch model. The resulting temporal discounting model did reasonably well in predicting choice time production *CV* data on the basis of choice RT and simple time production performance. The model's assumption that choice time production performance was dependent on the speed and reliability of the choice process was supported in Experiment 2, which demonstrated that choice RT practice attenuated the effects of the incompatible mapping on choice time production. In other words, the mere presence of attention demanding cognitive processes is not sufficient to determine the degree of impact on timing.

The temporal discounting model's assumption that the switch-open time is equal to the choice RT also implies that any nontiming process that is sufficiently long and variable will produce measurable changes in choice time production performance. For example, in the present experiments, the stimulus detection and response execution processes of the simple RT are considered as equally attention demanding as the response selection processes in the incompatible choice RT. This notion is contrary to the findings from PRP tasks (e.g., Lien & Proctor, 2002) as well as from dual-task timing studies that indicate that certain nontiming processes do not interfere with timing (e.g., Fortin & Breton, 1995). However, the latter report and other dual-task timing studies did not include analysis of timing variability and the scalar property, and so may reflect the influence of temporal discounting rather than an absence of attention demands. This issue can be resolved in future studies that examine the effects of different choice tasks, with speed and variability comparable to the present spatial choice task on choice time production speed and variability.

The temporal discounting model, described in the Appendix, quantifies the error correction process but does not specify the psychological processes involved. The results of Experiment 3 suggested that temporal discounting consisted of two processes—adjustment of timing by the use of feedback and by executive processing. However, how do these processes affect the internal clock? The progressive change in the choice time production mean across the first blocks of the task is consistent with the proposal that posttrial feedback updates the memory for the target interval (Meck, 1983; Meck & Benson, 2002), incrementally reducing the disparity between the produced interval and the target interval. Because temporal memory is a source of scalar variability (Gibbon et al., 1984), this mechanism is consistent with the temporal discounting model, which demands only that the shortened timing process in the choice time production task have the same *CV* as production of the original target interval in the simple time production task.

In contrast to feedback processing, the effect of executive temporal discounting is evident from the outset of the choice time production task when feedback is omitted. Although not necessarily inconsistent with memory adjustment, instant reductions in time production latency are the signature of increases to pacemaker rate (Lustig & Meck, 2005; Meck, 1983), as the temporal criterion is reached too early. It is possible that the choice time production task excites participants, increasing the pacemaker speed. Comparing performance in cases in which participants are and are not aware of the choice time production task before its commencement could test this hypothesis because the unanticipated task should be more arousing. This test would also help determine the extent to which this rapid temporal discounting is really "executive" in the sense of being the result of a deliberate strategy.

This executive form of temporal discounting could explain discrepancies between expected and observed effect magnitudes in other studies of attention and timing. An example of such a discrepancy occurred in a study in which the interaction of temporal and nontemporal memory was examined by combining a letter-matching task with a variable study set size with time production of a short (2-s) interval (Fortin et al., 1993). The RT increased 40 ms per study set item, but time production increased by 20 ms per item. In an experiment by Burle and Casini (2001), the difference between single-task and dual-task time production was somewhat less than the single-task RT and considerably less than the dual-task RT. In both cases, the differences may reflect participants' attempts to correct errors in anticipation of the dual-task condition (which did not otherwise provide feedback).

Perhaps the most novel aspect of the choice time production task was the use of an integrated signal that indicated to the participant when to start timing as well as the identity of the response. Experiments 4 and 5 separated the timing and choice stimuli and demonstrated that the choice time production mean increased as the SOA increased. A similar "gap location" effect was observed in the gap procedure (Fortin, 2003; Fortin & Masse, 2000), in which the timing mean increased with the delay between the onset of a timing signal and an interruption in the timing signal, during which no processing need occur. Taken together, the gap experiments and the SOA effect suggest that an increase in the mean is a general consequence of the operation of the internal clock's switch in anticipation of an interruption. In other words, the gap location and SOA effects are both instances of an "interruption location" effect. An interruption location effect was also observed in a time perception experiment (Casini & Macar, 1997) in which the delay to a task-relevant stimulus change altered the perceived interval duration.

Although results of these experiments as well as of others suggest that the putative internal clock switch accounts for the effects of attention both before and after an interruption in timing, the switch does not operate in the same way in these two cases. Theoretically, before an interruption, the switch opens briefly and periodically as the participant scans for the interrupting signal, whereas after an interruption, the switch remains open continuously until either attention-demanding processing is complete or the timing signal resumes (Buhusi, Sasaki, & Meck, 2002; Fortin, 2003; Fortin & Masse, 2000). That the switch can operate in different modes has been suggested previously as a means to unite timing and chronometric counting behavior in animals (Broadbent, Rakitin, Church, & Meck, 1993; Meck & Church, 1983). Moreover, the lack of an interaction between choice difficulty and the SOA effect in Experiment 5 also suggests that these two modes of switch operation are independent.

One important question is why temporal discounting minimized shifts in the mean as a result of choice difficulty (see Experiments 1–3) but not of SOA (see Experiments 4 and 5). One possible explanation can be found in a comparison of the SOA effects on the mean to Fortin's studies combining timing and memory scanning (Fortin et al., 1993), in which mean effects were also observed. Both the SOA in the present experiments and memory set size in Fortin's experiment varied from trial to trial. As a result, the expected average timing error varies from trial to trial as well. Participants may be less able to correct for these variable timing errors than for timing errors from between-participants manipulations in which the expected average timing error is constant from trial to trial. Consequently, temporal discounting in either form may be more difficult to carry out and less effective when attempted. On the basis of this interpretation, one might expect that adding feedback to Fortin's task may not completely attenuate the mean effect.

In conclusion, the temporal discounting model has implications for the study of timing and attention beyond understanding the relation between response timing and response choice to the extent that it makes predictions regarding the influence of attention on timing variability and provides a means of predicting the magnitude of changes to timing accuracy. Future applications of the temporal discounting model require that experiments enact two analyses. First, independent estimates of the secondary task RT should be compared with the difference between single- and dual-task time production. Disparities between these two values may indicate temporal discounting. Second, the impact of the secondary task on timing variability should be measured for at least two time intervals in order to detect violations of the scalar property. Such violations are indicative of serial processing and the operation of the internal clock's switch.

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Appendix

Formulation of the Temporal Discounting Model

Equations 1 and 2 specify the formulation of the temporal discounting model introduced in Experiment 1. The expected value of the response latency mean for choice time production trials is expressed in Equation 1.

$$E(\overline{M}^{ct}) = \overline{M}^{crt} + (\overline{M}^{tp} - \overline{M}^{crt}) \tag{1}$$

In Equation 1, $\overline{M}$ refers to the mean response latency. This value can be either the group- or within-participant cell mean, depending on the application. The superscripts refer to the task from which the average is obtained: *ct* for choice time production, *tp* for simple time production, and *crt* for choice reaction time. The operator $E()$ refers to the expected value of the enclosed quantity. Note that Equation 1 has not been reduced (by canceling the obtained choice reaction time means) because it is this version from which the expected value of the choice time production response time coefficient of variation (CV) is derived.

Equation 2 expresses how the expected value of the average choice reaction time $\overline{CV}$ is computed.

$$E(\overline{CV}^{ct}) = \frac{\sqrt{(\overline{M}^{crt}\overline{CV}^{crt})^2 + ((\overline{M}^{tp} - \overline{M}^{crt})\overline{CV}^{tp})^2}}{E(\overline{M}^{ct})} \tag{2}$$

The complex nature of the numerator of Equation 2 stems from the fact that the variance of a sum of independent random variables is the sum of the variances of the elements of the sum; $var(n + m) = var(n) + var(m)$, where $var()$ is the variance operator, n and m are random variables, and the covariance of n and m is zero (i.e., $cov[n, m] = 0$).

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