# EFFECTS OF MIXING STIMULUS DURATIONS ON TIME JUDGMENTS

by

PATRICIA A. D'ATENO

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|---|---|
| Date | Chair of Examining Committee<br>Bruce Brown |

| | |
|---|---|
| Date | Executive Officer<br>Joseph Glick |

Bruce Brown

Nancy Hemmes

Lanny Fields

Peter Balsam

Robert Allan

Supervision Committee

THE CITY UNIVERSITY OF NEW YORK

# Abstract

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by

PATRICIA A. D'ATENO

Advisor: Professor Bruce Brown

The effect of mixing stimulus durations on time judgments was examined in two experiments. All temporal judgments were obtained under dual-task conditions. In both experiments, stimulus duration and the context in which sample intervals were presented were manipulated in a mixed factorial design. In Experiment 1, two sample durations (12 and 24 s) were presented, while in Experiment 2 the number of sample durations was increased to three durations (6, 12, and 24 s). Sample durations were presented under both single and mixed duration conditions. Under the single duration condition, one sample interval was presented throughout an experimental session. Under the mixed duration condition, all the sample durations were presented in each experimental session. In both experiments, temporal judgments were shorter and standard deviations were smaller at the longest sample duration under the mixed duration condition when compared to the single duration condition. Relative measures of variability, coefficients of variation, did not differ between the two conditions. Moreover, flatter functions relating log temporal judgments to log sample duration were obtained under the mixed duration condition, although differences were significant only in Experiment 2. The flatter functions resulted from both a lower slope and higher intercept value under the mixed duration condition. These findings are discussed with respect to attentional clock models of timing.

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# EFFECTS OF MIXING STIMULUS DURATIONS ON TIME JUDGMENTS

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Investigations of human timing behavior have typically shown that temporal judgments of an interval vary depending upon the conditions under which those temporal judgments are obtained. One influence on timing behavior that has received much attention in timing research is the effect of presenting an additional task during the temporal judgment task. In these studies, temporal judgments obtained under single task (timing only) conditions are compared to those judgments obtained under dual task conditions. Under dual task conditions, participants judge the duration of the stimulus while they are performing an additional temporal or non-temporal task. For example, under the dual task condition, participants may judge the duration of a visually presented stimulus and read aloud a series of numbers that appear superimposed on the stimulus, whereas under the single task condition, participants judge the duration of the visual stimulus in the absence of the number reading task. Temporal judgments under dual task conditions tend to be shorter than temporal judgments obtained under single task, timing only conditions (e.g., Allan, 1998; Brown, 1997). There is also some evidence that the variability of temporal judgments is greater under dual task than under single task conditions (e.g., Brown, 1997).

Both of these dual task effects were obtained by Hemmes, Brown and Kladopolous (2004). In their study, both sample stimulus duration and presence/absence of a dual task were manipulated within subjects. Participants were presented with a green square that remained on a computer monitor for a predetermined amount of time. Under dual task conditions, a series of two-to-five digit numbers appeared superimposed in the center of the green square. Participants read each number aloud as it appeared. Temporal judgments were obtained under methods of estimation, reproduction, and production. Under the method of estimation, participants provided a verbal estimate the presented sample temporal interval. Under the method of reproduction, participants reproduced the presented sample temporal interval. Under the method of production, no sample stimulus was presented and participants were instructed to produce an interval of a specified duration (e.g., “Produce 10s.”).

For all three temporal judgment methods, under the single task, timing only conditions, temporal judgments were nearly veridical for the 2 s to 23 s range of sample stimulus durations. Under dual task conditions, the findings of Hemmes et al. (2004) differed in some respects across experiments and methods of obtaining temporal judgments. In general, under the methods of reproduction and estimation, sample durations longer than 10 s were underestimated relative to the single task condition. Additionally, the functions relating time judgments to sample stimulus duration were nonlinear. The obtained negatively accelerated functions indicated that the proportion of underestimation increased as sample duration increased. Additionally, when log transforms were taken for both axes, the slope of the log-log function was smaller under the dual task condition as compared to the single task condition. The variability of the untransformed temporal judgments was also influenced by the presentation of the additional task in the dual task conditions. For all three methods of obtaining temporal judgments, standard deviations of time estimates for individual participants were larger under dual task conditions as compared to single task conditions.

Although the shortening and increased variability of temporal judgments under dual task conditions are fairly typical findings (e.g., Brown, 1997), the negatively accelerated function relating temporal judgments to physical time is of particular importance to the present study. The negatively accelerated function is indicative of shortening that was not proportional at all sample duration values. That is, the proportion of shortening was larger at the longer sample durations.

There have been only a few studies that presented a range of sample durations similar to those presented by Hemmes et al. (2004). Most of those that did also found a flattening of slopes for the function relating temporal judgments to sample duration under a variant of the dual task condition, a multiple task condition (e.g., Brown & West, 1990; Brown, Stubbs & West, 1992). Under multiple task conditions, the number of tasks vary at values greater than two, whereas under dual task conditions, there are two concurrently presented tasks. In Brown and West (1990) and Brown, Stubbs and West (1992), participants were presented with a range of sample durations under conditions that differed in level of difficulty. The level of difficulty was manipulated by varying the number of additional concurrent tasks. The results of those studies reported overestimation of the shorter sample durations and underestimation of the larger sample durations. Brown et al. (1992), found a flattening of the slopes and an increasing of the y-intercepts of the functions relating log temporal judgments to log physical time as the number of concurrent tasks increased. These findings are consistent with the increasing degree of shortening evidenced by the negatively accelerated function obtained by Hemmes et al. (2004).

In an investigation of dual task difficulty, Hicks, Miller, Gaes and Bierman (1977) presented multiple sample intervals in two experiments. In Experiment 1, the level of task difficulty was manipulated by varying the level of uncertainty in a card-sorting task. Participants sorted decks of cards into one pile (0 bits of information), two piles based on color (1 bit of information) or four piles based on suit (2 bits of information). The level of response uncertainty, and therefore presumably difficulty, was thought to increase as bits of information increased. Each participant experienced each level of uncertainty plus a single task, control condition at each of three sample intervals, 8 s, 13 s and 22 s. Time judgments were obtained using the method of verbal estimation. The resulting time judgments represented overestimation of physical time at all sample intervals. Time judgments varied as a function of level of difficulty, with shorter judgments obtained under the more difficult dual task conditions. The authors do not report time judgments under each level of difficulty at each sample interval. The authors do report that the slope values of the functions relating time judgments to physical time were smaller for the color sort task (1.2) and the suit sort task (1.1) as compared to the single pile and control condition (1.3).

Similar flattening of slopes for the functions relating time judgments to sample duration were reported in two experiments that utilized a dual task involving memory (Hicks & Bundrige,1974; Hicks et al., Experiment 2, 1977). The range of sample duration values ( 8, 10, 14, 32, and 54 s) was larger in Hicks and Bundridge (1974), as compared to the sample duration values (8, 16 and 32 s) used by Hicks et al. (Experiment 2, 1977). In Hicks et al. (Experiment 2, 1977), the level of difficulty in the memory task was manipulated by varying the redundancy in letter strings that participants memorized at four levels (43%, 29%, 15%, and 0%). The level of task difficulty was said to increase as redundancy decreased. The slopes of the functions relating time judgments to sample duration were .872, .84, .732 and .752 for the 43%, 29%, 15% and 0% conditions, respectively. In Hicks and Bundridge (1974), timing under two memory conditions were compared to a single task (timing only) control condition. Time judgments were the same across the two memory conditions, and those temporal judgments were shorter than those obtained under the timing only control condition. The slope value for the functions relating temporal judgments to sample duration, under the memory conditions, .68, was smaller than the .94 slope value reported for the no-task condition.

Dual task difficulty was also manipulated by Sawyer, Meyers, and Huser (1994). In Experiment 1, participants made diagonal lines on a sheet of paper, crossed out letter A's that were presented in an array of letters, and solved four letter anagrams. There was also a single task control condition in which participants stared at a blank piece of paper. In Experiment 2, participants read aloud color label words printed in black ink, named the color of ink used to print asterisks, non-related words, and non-matching color words (Stroop task). In both studies, all task types were presented at each of three sample duration values, 14, 18 and 22 s, in a within subject manipulation. Results of both studies were similar in that time judgments varied as a function of sample duration and task type. Time judgments were underestimates of physical time under all conditions and decreased as task demand increased in both studies. Although the authors reported that there was no duration x task interaction, a visual analysis of the figures presented suggest that the slope values for the most demanding task conditions may be smaller than those for the least demanding and control conditions. Perhaps the lack of a significant duration x task interaction is related to the range of sample duration values presented. In Sawer et al. (1974) the range of sample duration values, 14 to 22 s, was smaller than those employed in the previously described studies.

These results of underestimation under dual task conditions as well as increasing degrees of underestimation with concomitant increases in task demand have inspired attentional models of timing. Generally, these models posit that timing is an attentionally demanding task. One such model, the attentional-gate model, proposed by Zakay and Block (1996) suggests the existence of some clock-type mechanism that includes an element that is regulated by attention to time. According to this model, time judgments are the product of a pacemaker that produces pulses at a rate that is based on arousal levels. The pulses are passed through an attentional-gate and a switch mechanism to a cognitive counter. The attentional gate is thought to operate in a graded fashion such that the opening can widen or narrow depending upon attention to time relative to other events. Under conditions of full attention to time, the opening of the gate is wide, whereas under conditions of competing events, the opening narrows. The number of pulses from the pacemaker that can pass through the gate to the switch are regulated by the size of the opening. Another conception of attentional gates posits that an attentional switch opens and closes or flickers at varying frequencies that are dependent upon attentional demand, allowing pulses to pass through to the accumulator in a graded fashion (Lejeune, 1998). Time judgments are based on the contents of the cognitive counter. According to this model, if attention is solely devoted to the timing task the attentional-gate will be open wider relative to conditions under which additional events, such as concurrent task stimulus events are present. This wider opening of the gate will result in more pulses accumulating in the cognitive counter, and therefore, larger temporal judgments relative to a narrower opening of the gate under concurrent task conditions.

A variation of this model, the attentional allocation model, was described by Brown (1997). This model is similar to the attentional-gate model in that time judgments are thought to be dependent upon attention to temporal events. According to the attentional allocation model, there is a limited pool of attentional resources, for which both the timing task and the concurrent task compete. Under concurrent task conditions, the competition for the limited pool of attentional resources results in time judgments that are shorter relative to single task, timing-only conditions.

Both of these attentional models can be accommodated as variants of the scalar timing model, which is an internal clock model of timing (e.g., Gibbon, 1991; Church, 1984). According to scalar or internal clock timing models, timing involves the operation of three processing components, an internal clock, memory, and decision-making components. In the clock component, pulses are emitted at some relatively constant rate. A switch either allows pulses to pass through, or blocks the passage of the pulses to an accumulator/working memory, the contents of which represents current subjective time. The contents of the accumulator can be compared to previously stored values in reference memory. A decision as to whether the contents in working memory are similar to the remembered time stored in reference memory is made by a comparator component. According to scalar timing models, subjective time grows as a linear function of physical time. Additionally, the largest sources of variability are thought to be scalar, based on the assumption that the values in the accumulator are transferred to reference memory under the control of a multiplicative constant that varies across storage occasions. Scalar variability implies that variability of time judgments (i.e., standard deviations) should be proportional to mean time judgments.

Scalar or internal clock timing models use the switch mechanism to accommodate the underestimation or shortening of time judgments under dual task conditions. That is, the operation of the switch mechanism is thought to be mediated by attention to the timing task. Under dual-task conditions, there would be interference in switch operation (an increased latency to open, increased switch-open time) that would result in fewer pulses passing to the accumulator and therefore, shorter temporal judgments relative to timing only conditions (Allan, 1998; Lejeune, 1998).

Some of the findings reported by Hemmes et al. (2004) are consistent with attentional clock models of timing. The finding that temporal judgments under single-task (timing only) conditions were linearly related to physical time is consistent with clock models. Findings that temporal judgments under dual-task conditions were underestimates of physical time are also consistent with an attentional clock. However, the finding of a curvilinear, negatively accelerated function relating temporal judgments to physical time under dual-task conditions, is not anticipated by these models, which would predict constant proportional underestimation across stimulus durations. Findings reported by Brown et al. (1992) of a flattening of slope the function relating log temporal judgments to log sample duration with an exponent less than 1, are likewise not consistent with clock models of timing. Brown and West (1990) reported temporal judgments that varied in a graded fashion from overestimation of the shorter to underestimation of the longer sample durations, a finding at variance with clock models that would predict identical proportion of underestimation at all sample durations. Moreover, the finding of overestimation of the shorter sample durations is not consistent with clock models of timing.

One common feature of those studies was the within subject manipulation of sample duration. Findings from two unpublished studies in which sample duration was manipulated between subjects showed proportional shortening of two sample intervals under dual-task conditions. D'Ateno (2001) and D'Ateno (2006) manipulated the rate of the same number-reading task used by Hemmes et al. (2004) at two sample intervals in a mixed design. In both studies, sample interval duration, 15 and 30 s, was manipulated between subjects and rate of task varied at three values in a within subjects manipulation. The studies differed in the specific rates of task presented. D'Ateno (2006) varied rate at lower levels than D'Ateno (2001). One of the rate conditions presented in D'Ateno (2006), the zero rate condition, was a condition in which no concurrent task (single task condition) was presented. With the exception of the zero rate condition, findings from both studies were similar in that resulting temporal judgments did not vary as a function of task rate. In D'Ateno (2001), mean temporal judgments were 10.7 s and 21.1 s for the 15 and 30 s sample intervals, respectively. Temporal judgments in D'Ateno (2006) for the two non-zero rate conditions, were slightly larger, 11.63 and 23.64 s for the 15 and 30 s sample intervals, respectively. In both studies, temporal judgments were shorter than physical time for both sample durations. Furthermore, in each study the degree of shortening was proportional across the different sample duration values. In D'Ateno (2001), mean temporal judgments represented .70 of physical time, whereas, in D'Ateno (2006), mean temporal judgments represented .78 of physical time. This proportional underestimation at both sample values is consistent with clock models but is not consistent with the previously described findings of Hemmes et al. (2004) of a negatively accelerated function.

One difference between these studies is exposure to more than one sample duration. All the studies that found nonproportional shortening exposed participants to multiple sample intervals. In contrast, proportional shortening was found under single sample interval exposure (D'Ateno, 2001; D'Ateno, 2006). Although the number of sample intervals was not manipulated, findings from a pilot study (D'Ateno, 2002) suggest that there may be some effect from experiencing more than one sample interval.

The D'Ateno (2002) study was a partial replication of D'Ateno (2001). The same experimental parameters were used as in D'Ateno (2001); however, sample interval duration was manipulated within subjects. The results were similar in that there was no effect of the task rate manipulation. Additionally, temporal judgments of both sample interval durations were underestimates of physical time. The degree of shortening, however, was not proportional. The mean time judgment for the 15 s sample was 12.16 s representing .81 of the sample interval, whereas the mean time judgment for the 30 s sample was 19.47 s representing .65 of the sample value. Although findings from these two studies cannot be directly compared, the finding of nonproportional shortening under conditions of multiple sample interval exposure is consistent with the previously described findings of Hemmes et al. (2004), with the smaller slope values for the log-log functions under dual task conditions reported by Brown et al. (1992), as well as with the findings from the other previously described studies that indicated possible increasing degrees of underestimation at the longer sample durations ( Brown & West, 1990; Hicks & Brundige, 1974; Hicks et al., 1977).

In the present study, the notion that exposure to multiple sample intervals may influence temporal judgments was explored in two experiments. In both experiments, stimulus duration and the context in which sample intervals are presented was manipulated in a factorial design. The experiments differed in the number of different sample durations. In Experiment 1, two sample durations, 12 and 24 s were presented, while in Experiment 2 the number of sample durations was increased to three (6, 12, and 24 s). In both experiments, all temporal judgments were obtained under dual task conditions. Sample duration values were presented under both single and mixed duration conditions. Under the single duration condition, one sample interval was presented throughout an experimental session. Under the mixed duration condition, multiple sample intervals were presented within each experimental session. All participants were exposed to both sample duration conditions.

The single duration condition was designed to mimic a between subjects manipulation of sample interval duration. It was expected that by restricting the mixing of durations and the presentation of the different duration values in the single duration condition to separate experimental sessions, any carryover effects from experiencing the different sample durations would be negligible in the single duration condition.

All temporal judgments were obtained under dual task conditions. As a typical finding in time judgment studies is underestimation or shortening of temporal judgments under dual task conditions (e.g., Brown, 1997), underestimation, relative to physical sample interval duration, is expected under both single and mixed duration conditions.

Previous studies (e.g., Hemmes et al., 2004) showed increased degrees of underestimation at the longer sample duration under the dual task condition. If exposure to multiple sample intervals is partly responsible for that increased degree of underestimation, then at the longer sample duration, shorter temporal judgments under the mixed condition as compared to the single condition are expected.

Temporal judgments were transformed as log scores to permit analyses of the slopes and intercepts of the log-log functions. If mixing of sample durations exerted some influence that contributed to the smaller slopes obtained by Hemmes et al. (2004) and Brown et al. (1992), under dual task conditions, then the slope for the mixed duration condition should be smaller than the slope obtained under the single duration condition. Additionally, temporal judgments were transformed as proportion scores (temporal judgment dived by sample duration) to examine effects of mixing sample durations on proportionality of temporal judgments. Previous unpublished observations showed that under single duration conditions, temporal judgments of two sample durations were proportional (D'Ateno, 2001; D'Ateno, 2006). Findings from Hemmes et al. (2004) of a negatively accelerated function revealed nonproportional temporal judgments of the seven sample durations that were presented. If mixing sample durations exerts some influence on the proportionality of temporal judgments, proportional temporal judgments may be expected under the single duration condition, whereas under the mixed duration condition, nonproportional temporal judgments would be expected.

Expectations for measures of variability are not clear, as the nature of any influence from mixing sample durations is unknown. One possibility that arises from the expectation that mixing durations will induce shortening of temporal judgments, is that mixing may act in a manner similar to a dual task which also induces shortening of temporal judgments. As one effect of a dual task is increased variability of temporal judgments, then measures of variability may be expected to be larger under the mixed duration condition.

# Experiment 1

## *Method*

*Participants.* Forty undergraduate Queens College students served as participants in partial fulfillment of an academic requirement. The only requirement for participation was not having previously participated in a time judgment study.

*Apparatus.* An IBM compatible 386 microcomputer with a VGA color monitor was used to present timing stimuli and collect data. All time values were programmed and recorded in milliseconds (ms) to an accuracy of plus or minus 55 ms. The left button of a Microsoft PS/2 mouse served as the manipulandum. A small tape recorder (Olympus model J300) was used to monitor participants' responses for the number-reading task.

*Experimental Design.* Two sample duration values were presented in two different experimental contexts in a mixed factorial design. The 12 and 24 s sample durations were either presented in a single duration condition, or a mixed duration condition. Under the single duration condition, one duration value was presented for all 20 trials in an experimental session. Under the mixed duration condition, both duration values were presented 10 times each during a 20- trial experimental session. The order of duration was block randomized in five blocks of size four. There were two orders of duration that were mirror images of each other, generated for the mixed duration condition. The order in which participants experienced each mixed condition order was balanced across participants in each group.

All participants experienced two single duration condition sessions and two mixed duration condition sessions. The order of single or mixed duration condition was balanced across participants. Half of the participants, the Single First Group, experienced the single duration condition sessions followed by the mixed duration condition sessions. The other half, the Mixed First Group, experienced the mixed duration condition sessions first followed by the single duration condition sessions. For the single duration condition sessions, the order of sample duration value, 12 and 24 s, was balanced across participants in each group. The four orders of duration and condition are presented in Table 1. Participants were assigned to conditions randomly. There were 20 trials in each session for a total of 80 experimental trials. Each duration value was presented 20 times under the single duration condition and 20 times under the mixed duration condition.

*Procedure.* Temporal judgments were obtained using the method of reproduction. On each trial, a green square, the sample stimulus, appeared on the center of a computer monitor for a predetermined duration. When the predetermined duration timed out, the green square was immediately replaced by a purple square. There was a 0-s delay between the sample and estimation stimulus. The participants' task was to terminate the purple estimation stimulus, using the left mouse button, when they estimated that the purple estimation stimulus had been visible for an interval equal to the duration of the green sample stimulus.

On all trials, a concurrent number-reading task was presented during the green sample stimulus. A series of two to four digit numbers appeared in the center of the green sample stimulus. Participants were instructed to read the numbers aloud pronouncing each place name. For example, the number 546 would be read “five hundred forty-six.”

The numbers were generated randomly with an equal probability (.33) of containing two, three or four digits. The duration of each digit was 400 ms. Therefore, the duration of each number was proportional to the number of digits. The duration of each number was either 800, 1200 or 1600 ms for the two, three and four digit numbers, respectively. The mean inter-number interval was 164 ms programmed with 40% variability (range: 98.4 - 229.6 ms).

*Training and Testing.* Participants were presented with a training session consisting of three trials prior to the four experimental sessions. During the training session, the duration of the green sample stimulus was 18 s. The concurrent-number reading task was present during training. No feedback was presented during training or testing. Instructions for the timing and number-reading tasks were presented on the computer monitor. The participants read the instructions and then verbally explained the task to the experimenter. The exact instructions presented to the subjects are included in Appendix A.

Following the training session, participants were presented with the four experimental sessions. A five-minute break was imposed between each experimental session. During the break, participants were required to leave the testing room.

### *Results*

For all analyses, time judgments were pooled across all sessions for each subject under each condition. Figure 1 depicts group mean time judgments as a function of sample stimulus duration for all participants in both the single and mixed duration conditions. The dotted line represents veridical time. These data show that under both conditions, time judgments were directly related to sample duration. Additionally, temporal judgments under both conditions were shorter than veridical time. The difference between veridical time and temporal judgments were evaluated with separate t-tests at the 12 and 24-s sample duration for each condition. Under the single duration condition, the mean temporal judgments were 1.53 s shorter (*t* (39) = 2.50, *p*<.02) for the 12-s and 7.59 s shorter (*t* (39) = 8.13, *p*<.0001) for the 24-s sample durations... Under the mixed duration condition, the mean temporal judgments were 1.45 s shorter (*t* (39) = 2.20, *p*<.03) and 8.68 s shorter ( *t*(39) = 9.95, *p*<.001) for the 12 and 24-s sample duration., respectively. .

The critical finding illustrated in Figure 1 is the difference in time judgments under the two conditions. At the 12-s sample duration, temporal judgments were virtually identical for both the single (10.47 s) and mixed duration (10.55 s) conditions. At the 24-s sample duration, however, a difference in temporal judgments was observed. The mean temporal judgment of 16.41 s under the single duration condition is larger than the mean judgment of 15.32 s under the mixed condition. A group (Single First, Mixed First) x duration (12, 24 s) x condition (single duration, mixed duration) ANOVA yielded a significant effect of duration, *F* (1, 38) = 187.41, *p* < .0001, a significant group x condition interaction, *F* (1, 38) = 5.77, *p* < .02, a significant condition x duration interaction *F*(1, 38) = 5.78, *p* < .02, and no other significant effects. (The ANOVA summary table can be found in Appendix A, Table A1). The condition x duration interaction was evaluated with separate repeated measures *t*-tests for each sample duration. The difference in temporal judgments between the single duration and mixed duration conditions at the 24-s sample duration was significant, *t* (19) = 3.18, *p* < .005, while the difference at the 12-s duration was not, *t* (19) = .31, *ns*. The effect size of difference at the 24-s sample duration, .35, was based on the proportion of variance accounted for by the manipulation based on t values (Heiman, 2000).

The group x condition interaction was evaluated by examining the effect of condition separately for each Group. Figure 2 shows mean temporal judgments as a function of Group for both the single and mixed duration conditions. These data appear to show that the effect of condition differed for the two Groups. For the Mixed First Group, temporal judgments appear to be larger under the single duration condition, whereas this difference was reversed for the Single First Group. These between condition differences were evaluated with separate repeated measures t-tests for each Group. For the Mixed First Group, temporal judgments were larger under the single duration condition as compared to the mixed duration condition, $t$ (39) = 3.52, $p < .002$. For the Single First Group, there was no significant difference in temporal judgments between the two conditions, $t$ (39) = 1.29, *ns*.

Standard deviations were calculated for each participant in each experimental session, under each condition. As each participant experienced two mixed duration sessions, two standard deviations were obtained for each sample duration in the mixed duration condition (e.g., one measure for each sample duration in each of the two sessions). The mean standard deviation for duration was then calculated for each subject. Figure 3 depicts mean standard deviations as a function of sample stimulus duration for both the single and mixed duration conditions. These data show that standard deviations varied as a function of condition and duration. Standard deviations were larger for the 24-s sample duration as compared to the 12-s sample duration. Additionally, there were larger differences in standard deviations between the 12 and 24-s sample durations for the single duration condition as compared to the mixed duration condition. At the 12-s sample duration, the standard deviation under the single duration condition was smaller than that in the mixed duration condition. In contrast, at the 24-s sample duration, the standard deviation under the single duration condition was larger than in the mixed duration condition. These differences can be seen in the relative steepness of the two functions. Under the mixed duration condition, the function relating mean standard deviations to sample stimulus duration appears flatter than the function for the single duration condition. A group x duration x condition ANOVA yielded a significant effect of duration, $F$ (1, 38) = 21.67, $p < .0001$, a significant condition x duration interaction, $F$ (1, 38) = 6.45, $p < .02$, and no other significant effects. (The ANOVA summary table is presented in Table A2 in Appendix A). The condition x duration interaction was evaluated with separate t-tests at each sample duration which yielded a significant difference at the 24-s sample duration, $t$ (39) = 2.43, $p < .05$, and no significant difference at the 12-s sample duration, $t$ (39) = .91, *ns*.

Relative measures of variability were also analyzed. Coefficients of variation (CV scores) were calculated for each participant under each condition. The temporal judgments and standard deviations used for calculating the CV scores under the mixed duration condition were averaged across all mixed duration sessions (i.e., individual calculations of CV scores were not obtained for each mixed duration session). Table 2 shows mean CV scores under each condition at each sample duration value. These data show that under both the single and mixed duration conditions, the CV scores were larger at the 12-s sample duration as compared to the 24-s sample duration. The mean CV scores were .2574 and .2208 for the 12-s and 24-s sample durations, respectively. A group x duration x condition ANOVA yielded a significant effect of duration, $F$ (1, 38) =

8.06, *p* < .007, and no other significant effects. (The ANOVA summary table can be found in Table A3 in the Appendix).

Each time judgment for each subject was converted to a common log score. As some time judgments were values less than 1 s, prior to the log transformation, all time judgments were subjected to a multiplicative transform by a factor of ten for purposes of statistical analyses. Mean log scores were then calculated for each subject under each condition. The reported log scores were corrected for the multiplicative transform by subtracting 1 log unit from the mean log scores. Figure 4 displays these mean log scores as a function of log sample stimulus duration. Mean log scores were directly related to sample stimulus duration. Although it appears that the functions for the two conditions differ at the 24-s sample duration, statistical analyses showed that there were no significant differences as a function of condition. A group x duration x condition ANOVA yielded a significant effect of duration, *F* (1, 38) = 302.62, *p* < .0001, a significant condition x group interaction, *F* (1, 38) = 6.82, *p* < .01, and no other significant differences. (Table A4 Appendix A shows the ANOVA summary table for the log score analysis). A regression analysis of the log time judgments was also conducted. Although the obtained slope value under the single duration condition of .89 was larger than the slope value of .77 obtained under the mixed duration, this difference was not significant, F(1, 38) = 3.31, *ns*. Likewise, the intercept value of .02 for the single duration condition did not differ from the .15 value obtained under the mixed duration condition, F(1, 38) = 2.52, *ns*.

Temporal judgments were also transformed into proportion scores (temporal judgments divided by sample duration value). Table 3 shows proportion scores for both sample duration values, under each condition. These data show that under both conditions, proportion scores were larger at the 12-s duration as compared to the 24-s condition. A group x condition x duration ANOVA yielded a significant effect of duration, *F* (1, 38) = 93.31, *p*< .0001, a significant condition x group interaction, *F* (1, 38) = 6.56, *p*< .01, and no other significant effects (Table A5 Appendix A shows the ANOVA summary table for the proportion score analysis). The condition x group interaction is illustrated in Figure 5. These data show that proportion scores were larger under the mixed condition for the Single First Group, whereas, for the Mixed First Group, larger proportion scores were obtained under the single condition. These between condition effects were evaluated with separate t-tests for each Group. For the Mixed First Group, the proportion scores were significantly larger under the single condition as compared to the mixed condition, *t* (39) = 3.34, *p*< .01. For the Single First Group, however, there were no significant differences between the two conditions, *t* (39) = -1.87, *ns.*

### *Discussion*

With respect to the experimental predictions, the critical finding in Experiment 1 was the condition x duration interaction obtained for time judgments. The mean time judgments were shorter under the mixed duration condition as compared to the single duration condition at the longer sample duration, but not at the shorter duration. This finding is consistent with the notion that exposure to multiple sample durations exerts some influence on temporal judgments.

The group x condition interaction showed that the order of conditions differentially influenced temporal judgments. That is, for the group that experienced the mixed duration condition first, temporal judgments were larger under the single duration condition as compared to the mixed duration condition. Differences across conditions were not found for the group that experienced the single duration condition first. It is difficult to interpret this interaction as there is a confound between conditions and the sequence of conditions. It is possible that the interaction reveals sequence effects. If time judgments increased across experimental sessions, and the mixed duration condition influences shortening of temporal judgments, then differences across the two groups would be expected. For the Single First Group, the lack of difference between the conditions might have resulted from temporal judgments that both increased across sessions and decreased under the mixed duration condition that was experienced last. The two influences, session and condition might have cancelled each other out. In contrast, for the mixed first group, the single duration condition was experienced last and so increases in temporal judgments as a function of session would have magnified the differences under the two conditions. Although sequence effects may be a possible explanation, a post hoc analysis comparing all temporal judgments from the first two sessions to those obtained in the last two sessions showed that the seemingly longer judgments obtained in the last two sessions did not differ significantly from those obtained in the first half of the experimental sessions.

The findings for standard deviations were similar to those for temporal judgments. Consistent with Hemmes et al. (2004), standard deviations varied directly with sample duration. That is, standard deviations were larger for the 24-s sample as compared to the 12-s sample duration. Additionally, the condition x duration interaction showed that standard deviations were smaller at the 24-s sample duration under the mixed duration condition as compared to the single duration condition. Relative measures of variability, CV scores, did not differ as a function of condition.

The transformation of time judgments to log scores permitted analyses of both the log transformed time judgments as well as an examination of slopes and intercepts for both the single and mixed conditions. Findings from the log transformed time judgment analyses differed from the untransformed time judgment analysis in that there was no condition x duration interaction. Although differences in log time judgments were not significant, the functions for the single and mixed conditions appear to differ in a pattern similar to that for the untransformed time judgments. The regression analyses of those log time judgments showed that the slopes and intercepts for the single and mixed conditions did not differ significantly. Although the differences in slopes were not significant, the slope values were in the anticipated direction. That is, the slope value of .89 for the single duration condition appears to be larger than the .77 value obtained under the mixed duration condition. Perhaps the lack of a significant difference in the present study might be due to having only two sample duration values. Previous studies of interference effects that have found flattening of the function relating log time judgments to log stimulus durations (Brown, Stubbs & West, 1992; Hemmes et al., 2004) have employed more than two sample duration values. However, the manipulations in those studies differed from that in the present study.

Analyses of time judgments relative to physical time were also conducted. Both the direction and the relative degree of difference of temporal judgments from physical time were evaluated. Consistent with previous research of temporal judgments under dual task conditions, temporal judgments of both sample durations under both conditions were shorter than physical time (e.g., Brown, 1997). Additionally, the relative degree of difference of temporal judgments from physical time was examined by transforming temporal judgments into proportion scores. Previous observations suggested that when only one sample duration was presented to a participant (i.e., between subjects manipulation of sample duration), temporal judgments of those sample durations were proportional (D'Ateno, 2001). In contrast, studies in which multiple sample durations were presented to each participant found that temporal judgments were not proportional across the different sample durations (Hemmes et al., 2004). One experimental hypothesis arising from these findings was that under the single duration condition, temporal judgments would be proportional. This prediction was not supported by the present findings. For both the single and mixed conditions, proportion scores differed at the two sample durations. There was, however, a significant condition x group interaction. The pattern for this interaction is the same as the interaction found for the untransformed temporal judgments. The evaluation of this interaction is difficult due the confound between the order of conditions and Group that was previously discussed for the untransformed temporal judgments. Perhaps the lack of a significant difference in proportion scores might be due to the small range of sample durations employed in the present study.

## Experiment 2

Findings from Experiment 1 suggest that exposure to multiple sample durations exerts some influence on temporal judgments. The influence of multiple sample durations, however, appears to be small. Differences in temporal judgments between the single and mixed duration conditions were limited to a difference of 1.09 s at the 24-s sample duration. Findings from the log-transformed data did not reveal differences between the single and mixed conditions. Although the log-log functions showed a flatter function for the mixed duration condition as compared to the single duration condition, the slopes and intercepts of those functions did not differ significantly. One possible basis for the small effects of multiple sample durations found in Experiment 1 might be the limited range of sample durations that were employed. Therefore, Experiment 2 was designed with a larger range of sample durations. The design of Experiment 2 was the same as Experiment 1, with three sample duration values, 6, 12 and 24 s. The addition of a third sample duration required changes from Experiment 1 in the number of experimental sessions and number of trials with each sample duration. The design for Experiment 2 included three single duration and three mixed duration experimental sessions with 18 trials in each session. If the range of sample durations influences the effects of exposure to multiple sample durations, then it is expected that experimental effects will be larger than those found in Experiment 1. Specifically, it is expected that the findings for temporal judgments will be replicated. Additionally, it is expected that the log-log function for the mixed duration condition will be flatter as compared to the single duration condition.

*Method*

*Participants.* Forty-two undergraduate Queens College students served as participants in partial fulfillment of an academic requirement. Of the forty-two participants, only data from thirty-six participants were used in the analyses. The study was designed for thirty-six participants. The last six participants were run as possible replacements for participants that were removed. Three of the original thirty-six participants were removed from the final analyses for different reasons. One participant did not follow directions and utilized paper and pencil during the time judgment task. Data from two of the participants were discarded due to extreme deviation (more and less than 3 standard deviations from the mean) from the other participants. The slope of the log transformed time judgments was less than 3 standard deviations from the mean for one participant, whereas the intercept of log transformed time judgments was greater than 3 standard deviations from the mean for the other participant. These three participants were replaced by three of the replacement participants. Data from the other three replacement participants were not included in the final analyses.

*Apparatus.* The same apparatus described for Experiment 1 were used for Experiment 2.

*Experimental Design.* The experimental design and procedure of Experiment 2 was identical to Experiment 1 with exceptions in the numbers of sample duration values, experimental sessions and trials per session. Three sample duration values, 6, 12 and 24 s, were presented in mixed factorial design. . Each duration value was presented in both mixed and single duration conditions. Under the mixed duration condition, each sample duration was presented six times for a total of 18 trials per experimental session. The order of duration was block randomized in three blocks of size six. Three different block randomized duration orders were generated.

All participants were exposed to three consecutive single duration sessions and three consecutive mixed duration sessions. As in Experiment 1, the order of single or mixed duration sessions was balanced across participants. For the single duration sessions, the order of sample duration value, 6, 12 and 24 s was determined by a latin square. The six orders of duration and are presented in Table 4. There were six participants assigned to each row of the latin square. There were 18 trials in each session for a total of 108 experimental trials. Each sample duration was presented 18 times under each condition.

*Training and Testing*. During the three-trial training session, a 14-s sample duration was used in Experiment 2. The training sample duration value represents the mean of the three sample duration test values. The procedures during testing were identical to those described in Experiment 1. Six experimental testing sessions immediately followed the training session.

The testing procedure was identical to that described for Experiment 1. A green sample stimulus was presented in the center of a computer screen for a predetermined duration. When the duration of the sample stimulus timed-out, a purple estimation stimulus appeared in the same location. There was a 0 s delay between the offset of the sample and onset of the estimation stimulus. Participants terminated the purple estimation stimulus, by depressing the left mouse key, when they estimated the duration of the estimation stimulus was the same as the sample stimulus.

The next estimation stimulus appeared when the participants depressed the mouse key. At the conclusion of all 18 trials in an experimental session, instructions to call the experimenter appeared on the computer screen. A 5-minute break, during which the participant left the experimental room, was imposed between each experimental session. As in Experiment 1, a number-reading task was presented during all sample stimuli. The parameters of the stimuli in the number-reading task are identical to those used in Experiment 1.

### *Results*

The data from Experiment 2 were analyzed in the same manner as for Experiment 1. Group mean time judgments for all participants under each condition are shown as a function of sample stimulus duration in Figure 6. Consistent with findings from Experiment 1, temporal judgments varied directly with, and were underestimates of, sample stimulus duration. The departure of temporal judgments from sample duration for all sample durations was evaluated with separate t-tests at each sample duration under each condition. These tests yielded significant departures from physical time for all temporal judgments. Table 6 shows the statistics from all t-tests.

Figure 6 shows that the difference in time judgments between conditions increases with sample duration. However, consistent with Experiment 1, temporal judgments under the two conditions differed only at the longest sample duration. At the 24-s sample duration, the mean temporal judgment under the mixed duration condition was shorter (14.34 s) than the time judgment obtained under the single duration condition (16.19 s). A group (Single First, Mixed First) x duration (6, 12, 24 s) x condition (single duration, mixed duration) ANOVA yielded a significant effect of duration, $F$ (2, 68) =

165.37, $p < .0001$, a significant effect of condition, $F\ (1, 34) = 6.57$, $p < .02$, and a significant condition x duration interaction, $F\ (2, 68) = 9.13$, $p < .0003$. The ANOVA summary table is shown in Appendix B, Table B1. The main effect of condition was qualified by the condition x duration interaction. The condition x duration interaction was evaluated with repeated measures t-tests at each sample duration. Differences in time judgments between the conditions at the 6 and 12-s sample durations were not significant, $t\ (11) = .08$, *ns*., and $t\ (11) = 1.37$, *ns*, respectively, whereas a reliable difference was found at the 24 s sample duration, $t\ (11) = 4.85$, $p < .002$. The effect size of this difference at the 24-s sample duration, .70, was based on the proportion of variance accounted for by the manipulation based on t values (Heiman, 2000).

Standard deviations were calculated for each subject, under each condition, in each experimental session. Figure 7 depicts mean standard deviations as a function of sample stimulus duration for the single and mixed duration conditions. These data show that standard deviations varied as a function of sample stimulus duration. In addition, standard deviations appear to be larger for the single duration condition as compared to the mixed duration condition. The difference in standard deviations between conditions seems to increase as sample duration increases. A group (Mixed First, Single First) x duration (6, 12, 24 s) x condition (mixed duration, single duration) ANOVA yielded a significant effect of duration, $F\ (2, 68) = 60.88$, $p<.0001$, a significant effect of condition, $F\ (1, 34) = 9.92$, $p < .003$, a condition x group interaction, $F\ (1, 34) = 5.34$, $p > .03$, and a significant condition x duration interaction, $F\ (2, 68) = 5.21$, $p <.008$. The ANOVA summary table is shown in Appendix B, Table B2.

The main effect of condition revealed that standard deviations were larger for the single condition, 2.39, as compared to the mixed condition, 2.05. This main effect was, however, qualified by the condition x group and condition x duration interactions. The condition x duration interaction was evaluated using separate *t*-tests at each sample duration value. Differences at the 6 and 12-s sample durations were not significant, $t$ (11) = .31, *ns.* and $t$ (11) = 1.46, *ns.* Only the difference at the 24-s sample duration value was significant, $t$ (11) = 3.95, $p < .01$.

The condition x group interaction was evaluated with separate repeated measures *t*-tests for each Group. Standard deviations were larger under the single duration condition as compared to the mixed duration condition for the Mixed First Group, $t$ (53) = 5.49, $p < .002$, however, the difference between conditions was not significant for the Single First Group, $t$ (53) = .84, *ns.*

Coefficients of variation (CV) scores were also calculated for each subject under each condition. Table 5 shows mean CV scores for each condition at each sample duration. Although CV scores appear to be larger for the Mixed Duration condition at all sample duration values, a group x condition x duration ANOVA yielded no significant main effects or interactions. The ANOVA summary table is shown in Appendix B, Table B3.

Time judgments were transformed into common log scores. As some time judgments were less than one second, each participants' time judgment on every trial were multiplied by 10 prior to the log transformation for purposes of statistical analyses. The reported log scores were corrected for the multiplicative transform by subtracting 1 log unit from the mean log scores. Figure 8 shows mean log time judgments as a function of log sample stimulus duration. These data show that log time judgments varied directly with log sample stimulus duration. Log time judgments appear to be larger under the single as compared to the mixed duration condition at the longer sample durations. A group x condition x duration ANOVA yielded a significant effect of duration, $F\ (2, 68) = 399.15$, $p < .0001$, a significant condition x duration interaction, $F\ (2, 68) = 3.54$, $p < .04$, and no other significant effects. The ANOVA summary table is shown in Appendix B, Table B4. The condition x duration interaction was evaluated with repeated measures t-tests at each sample duration value. The differences between conditions at the 6 and 12-s sample duration values were not significant, $t\ (11) = -.21$, *ns*. and $t\ (11) = 1.66$, *ns*., respectively. At the 24-s sample duration value, however, the log time judgments under the single duration condition were significantly larger than the log time judgments obtained under the mixed duration condition, $t\ (11) = 3.18$, $p < .01$.

The log time judgments displayed in Figure 8 show that the function for the mixed duration condition appears to be flatter than the function for the single duration condition. A regression analysis of the group mean log time judgments showed that both the single and mixed functions were linear. The r-squared values for the group functions were .99 for both the single and mixed conditions. In addition, r-squared values were calculated for each subject under each condition. The mean r-squared values calculated from the individual subject data were .93 and .95 for the single and mixed conditions, respectively. The log-log functions for each subject were subjected to a linear regression analysis, and group mean slopes and intercepts were compared between the two conditions. The group mean slope value for the single duration condition, .90, was significantly larger than the mean slope value of .80 obtained for the mixed duration condition, $F(1, 34) = 9.09$, $p < .005$. The mean intercept under the single duration condition was -.98, whereas, the mean intercept under the mixed duration condition was .05. The difference between the intercepts of .07 log units was significant, $F(1, 34) = 4.11$, $p < .05$.

Temporal judgments were also transformed into proportion scores (temporal judgment dived by sample duration). Table 7shows the mean proportion scores at each sample duration for both conditions. For both the single and mixed conditions, mean proportion scores varied inversely with sample duration. There seems to be a more marked decrease in proportion scores as a function of sample duration under the mixed condition as compared to the single duration condition. A group x condition x duration ANOVA yielded a significant effect of duration, $F(2, 68) = 58.52$, $p < .0001$, a marginally significant condition x duration interaction, $F(2, 68) = 3.04$, $p < .0545$, and no other significant effects. The ANOVA summary table is shown in Appendix B, Table B5.

### *Discussion*

Findings from Experiment 2 were consistent with those from Experiment 1 related to time judgments and measures of variability. Similar to Experiment 1, temporal judgments for the longest sample duration were shorter under the mixed duration condition as compared to the single duration condition. This increased shortening is consistent with the negatively accelerated function obtained under the dual task condition reported by Hemmes et al. (2004).

Findings for measures of variability, standard deviations, were similar to findings from Experiment 1. Standard deviations increased as a function of sample duration. Additionally, the condition x duration interaction revealed that standard deviations varied with condition at the longest sample duration. That is, standard deviations were smaller under the mixed condition as compared to the single condition, at the 24-s sample duration. These findings are similar to those for the temporal judgment analysis. Consistent with findings from Experiment 1, relative measures of variability, CV scores, did not vary as a function of condition. In contrast to findings from Experiment 1, CV scores did not vary across sample durations.

The log score and regression analyses revealed differences across the two conditions. At the 24-s sample duration, log time judgments were shorter under the mixed duration condition as compared to the single duration condition. In addition, slopes and intercepts of the functions relating log time judgments to log sample duration varied between the two conditions. The flatter function obtained under the mixed duration condition resulted from both a smaller slope and larger intercept compared to the single duration condition.

Consistent with Experiment 1, proportion scores differed across sample durations for both the single and mixed conditions. Although the proportion scores decreased as a function of sample duration, the decrease seemed to be slightly larger for the mixed duration condition as compared to the single duration condition. The finding of differences in proportion scores for the single duration condition is not consistent with expectations based on previous unpublished observations that showed proportional temporal judgments under dual task conditions with a single sample duration (D’Ateno, 2001; D’Ateno, 2006). In the previous studies, participants experienced only one sample duration throughout the entire experiment. In the present study, participants experienced some single sample duration sessions, but across all sessions they were exposed to all sample durations. The absence of constant proportional underestimation in the single duration condition may have been related to the exposure of all subjects to multiple sample duration values across all experimental sessions.

# General Discussion

Effects of the number of sample duration values on time judgments were investigated in the present study. Under the single duration condition, one sample interval value was presented during an entire block of trials, i.e., experimental session. Under the mixed duration condition, more than one sample interval value was presented within a session. In Experiment 1, there were two sample duration values, 12 and 24 seconds, whereas in Experiment 2, a third value of 6 seconds was used in addition to the 12 and 24 second values employed in Experiment 1.

In the present study, temporal judgments of all durations under both the single and mixed conditions were underestimates of physical time. This finding of underestimation was expected as all temporal judgments were obtained under dual task conditions. Much previous research has shown that one effect of a dual task is shortening of temporal judgments relative to timing-only conditions (e.g., Brown, 1997), as well as relative to physical time (Hemmes et al.,2004).

In addition to shortening at all durations under both conditions, differential shortening between the conditions reveals evidence of effects that arise from the presentation of multiple sample durations within a session. In both experiments, temporal judgments of the longest sample duration, 24 seconds, were significantly shorter under the mixed duration condition as compared to the single duration condition. The differences in time judgments between the two conditions were 1.09 and 1.85 s in Experiments 1 and 2, respectively.  Although this effect was small in absolute terms, the findings were consistent across both experiments and amounted to a 5-8% difference in time estimates.

Insofar as mixing of sample durations was associated with increased shortening, perhaps mixing influenced the level of difficulty. That is, perhaps the mixed duration condition was more difficult than the single duration condition. There has been much previous research that investigated effects of manipulating parameters of the dual task condition, such that some dual task (or multiple task) conditions were thought to be more difficult, or associated with higher levels of dual task demand than others (e.g., Brown, 1997; Brown et al. 1992; Hicks, Miller, Gaes & Bierman, 1977; Sawyer, Meyers & Huser, 1994). Findings from these studies generally show that temporal judgments vary with the level of "task difficulty," such that the magnitude of typical dual task effects increase as values of task demand or task difficulty increases. These dual task effects include both shortening of temporal judgments as well as increased variability of those judgments (e.g., Brown, 1997). Both Brown, 1997 and Brown et al., (1992) reported graded effects of increased task demand on both temporal judgments as well as measures of variability (standard deviations and coefficients of variation). In the present study, findings for shortening of temporal judgments are consistent with this interpretation of increased difficulty for the mixed duration condition. Findings for measures of variability, however, are not consistent with this interpretation. If mixing increased the level of difficulty, then measures of variability would be expected to be larger under the mixed condition relative to the single duration condition. Conversely, in the present study, standard deviations were smaller under the mixed duration condition as compared to the single duration condition at the longest sample duration. At the shorter sample duration values, there were no differences in standard deviations between the mixed and single duration conditions. Relative measures of variability, CV scores, did not differ between the two conditions, indicating that means and standard deviations of time judgments varied together for both conditions. Insofar as typical effects of increased difficulty are associated with both increased variability of temporal judgments as well as decreased mean judgments, the mixing of stimulus durations appears to act in a functionally different manner.

Although there were no differences in CV scores as a function of condition in the present studies, there was some discrepancy in the two experiments with respect to differences as a function of sample duration. In Experiment 1, CV scores were larger for the 12-s sample duration as compared to the 24-s sample duration. In contrast, CV scores did not differ across the three sample duration values in Experiment 2. The interpretation of CV scores varies for different timing models. According to scalar timing models that include attentional and clock models of timing, CV scores should be invariant across differences in sample duration value. Alternatively, the behavioral theory of timing (BET; Killeen and Fetterman, 1988; Killeen & Weiss, 1987) would not predict stable CV scores across varying sample duration values. According to Killeen and Weiss, the contribution of an underlying Poisson process in the timing mechanism would result in CV scores that would decrease nonlinearly as sample duration values increase.

One way in which participants’ behavior might influence CV scores would be the strategy used for making temporal judgments. Hinton and Rao (2004) showed that when participants were instructed to chronometrically count during a temporal interval, CV scores decreased as a function of sample duration, whereas, when participants were instructed not to chronometrically count, CV scores were constant across a range of sample durations. Presumably, under the dual task conditions used in the present study, participants are prevented from chronometrically counting, whereas, under timing-only conditions, participants can use chronometric counting to mediate temporal judgments. Unpublished data from the laboratory of Hemmes and Brown, which used a dual task condition similar to the one used in the present study, lend support to these differences based on counting. CV scores decreased less under dual task conditions as compared to timing-only conditions. In the present study, presumably chronometric counting was prevented due to the presence of the concurrent number-reading task, an inference that is consistent with stable CVs across durations in Experiment 2. The finding that CV scores did vary as a function of sample duration in Experiment 1 might be due to the narrower range of sample duration values in Experiment 1 as compared to Experiment 2.

The log transformation of temporal judgments permitted analyses of slopes and intercepts of the function relating log temporal judgments to log stimulus duration. The slope of the log-log function has been interpreted as a measure of sensitivity to changes in physical sensation. Flatter functions with lower slope values would indicate reduced sensitivity (Stevens, 1960).

In the present study, the analyses of the log transformed temporal judgments, was consistent with the notion of reduced sensitivity under the mixed duration condition compared to the single duration condition. In both experiments, flatter functions relating log time judgments to log sample duration were obtained under the mixed condition, although differences were significant only in Experiment 2. In Experiment 2, the flatter function resulted from both a smaller slope value and a larger intercept value for the mixed duration condition. Slope values of .89 and .80 were obtained under the single and mixed duration conditions, respectively. The group mean intercept value for the mixed condition was .07 log units larger than for the single duration condition. Differences in slopes and intercepts were not significant in Experiment 1; however, they were in the same direction as for Experiment 2 (i.e., lower slope and larger intercept values for the mixed duration condition). In Experiment 1, slope values of .89 and .77 were obtained under the single and mixed duration conditions, respectively. The group mean intercept value for the mixed duration condition was .13 log units larger than for the single duration condition.

If an effect of mixing durations were a reduction in sensitivity to sample duration, then a lower slope value under the mixed condition relative to the single condition would be expected. In the present study, the smaller slopes and larger intercepts were obtained as a result of mixing sample durations. Dual tasks have also been associated with flattening of log-log functions. Brown, et al. (1992) obtained similar findings for slopes and intercepts that were influenced by dual tasks involving multiple timing conditions. Hemmes et al. (2004) also found that under dual task conditions, slope values were smaller compared to timing-only conditions. In both of those studies, temporal judgments under dual or multiple task conditions were less accurate and more variable than temporal judgments obtained under timing-only conditions. When those temporal judgments were plotted on log-log axes, the lower slope values for the less accurate temporal judgment functions indicated decreased sensitivity to differences in sample duration values. The locus of this decreased sensitivity has been the subject of discussion in research investigating timing performance.

An attentional clock model of timing may be used to examine sensitivity of timing performance. According to these models, during a time judgment task, temporal information is gathered during the presentation of a sample stimulus, and this information is compared to previously gathered information that is stored in reference memory. Therefore, making a time judgment involves the gathering of the temporal information, storing the temporal information in reference memory and then retrieving the information from the reference memory store. Brown et al. (1992) distinguished between two phases of a time judgment task, an input and an output phase. The input phase involves the gathering of temporal information, while the output phase involves the storage and retrieval of the stored information.

Hemmes et al. (2004) discussed the possibility that the flatter function obtained under the dual task condition might be due to differential sensory input under single task conditions and dual task conditions. According to that account, under single task conditions, participants were able to count during the temporal judgment task. Therefore, temporal judgments were likely based on sensory input from this counting behavior. In contrast, under dual task conditions, participants are not able to count. Therefore, temporal judgments under dual task conditions are based on some other (non counting) sensory input. Timing performance would therefore, be controlled by different sensory dimensions under single task conditions versus dual task conditions. Although it could be argued that mixing is similar to a concurrent task in influencing flattening of the log-log function, there are a couple of factors that would mitigate that argument. First, in Hemmes et al. (2004), dual task performance was compared to single task performance. In the present study, as the same dual task was present in both the single and mixed duration conditions, presumably timing performance was controlled by the same sensory dimension in both conditions. Second, as previously discussed, mixing does not appear to function as a concurrent task with respect to measures of variability. Therefore, it is unlikely that the locus of the mixing effect is in the input phase.

The locus of the mixing effect might more likely be in the output phase in which temporal information is stored and retrieved from reference memory. That is, perhaps the differential sequence of temporal stimuli in the single and mixed duration conditions, influenced memory mechanisms. An examination of the timing task used in the present study may elucidate how the sequence of temporal stimuli might influence memory mechanisms. During a reproduction-type timing task as was used in the present study, a subjective representation of temporal information gathered during the sample stimulus is represented in the accumulator, subsequently transferred and stored in reference memory. One might suppose that during the reproduction phase, the temporal information in the accumulator represents current elapsed time of the reproduction stimulus. When a match is made between current elapsed time and a retrieved reference memory of the sample stimulus time, the participant terminates the reproduction stimulus, thereby indicating their temporal judgment of the sample stimulus.

The integrity of this system depends upon accurate storage to, and retrieval from, reference memory. In a situation with multiple sample stimulus durations, there may be a problem with temporal stimulus control due to different reference memory stores that correspond to different sample stimulus durations. Given that system, one could conceive of two extreme types of outcomes. At one extreme, if values were stored and retrieved from reference memory perfectly, there would be a maximum degree of stimulus control by time. At the other extreme, if values were stored and retrieved from reference memory at random, there would be an absence of stimulus control by time. In the present study, the observed performance for both the single and mixed duration conditions falls somewhere in between the two extremes. Performance was, however, better under the single as compared to the mixed condition. The expectation of better performance for the single duration condition could be made from the operation of this type of system. That is, in the single duration condition, owing to the absence of a requirement for different reference memory stores, it might be expected that the reference memory stores would contain more homogeneous contents relative to the mixed duration condition. The more homogeneous reference memory stores would lead to an expectation of better stimulus control under the single duration condition.

Ideas like this have been usefully applied in some timing literature. Penny, Gibbon and Meck (2000) suggested that “memory mixing” might account for differences in temporal judgments of visual and auditory stimuli. In that study, temporal judgments did not differ between the modality conditions when only one modality was presented in an experimental session. Differences in which auditory stimuli were judged longer than visual stimuli were obtained when stimuli from both modalities were presented during an experimental session. The authors argued that memorial representations of the visual and auditory cues became “mixed” when stimuli from both modalities were presented during the same experimental session. Wearden, Todd, and Jones (2006) argued that representations for auditory stimuli were presumably longer than those for visual stimuli of the same physical duration owing to a faster clock rate under the auditory condition. When these two representations became mixed, the resulting representation was some intermediate value. These authors found that effects of memory mixing could be mitigated by experimental procedures that enhanced the differentiation of auditory and visual stimuli in a bisection procedure (Wearden, Todd & Jones, Experiment 1, 2006). The enhancement of modality differentiation presumably precluded mixing of memories for the different modalities. “Memory mixing” might be applied to some of the findings in the present study. In the present study, the reproduction-timing task might occasion the establishment of reference memories during the experimental session. If mixing of subjective judgments for different sample durations can occur in a manner similar to mixing of judgments from different modalities, perhaps some of the present findings for the mixed condition could be ascribed to memory mixing. Findings for variability measures in the present study, however, are not consistent with the notion of “memory mixing” or incorrect storage/retrieval from memory. It would seem likely that those effects on memory mechanisms would lead to larger amounts of variability. Conversely, in the present study, measures of variability were smaller for the mixed condition relative to the single duration condition.

The notion that some parameters of stimulus presentation may alter perceived judgments of those stimuli has been discussed in classic psychophysical literature. In these psychophysical studies, participants make some type of judgment as to the magnitude of the presented stimulus. When the log values of those judgments are plotted as a function of log stimulus intensity, the derived exponent of the log-log function is thought to be a measure of sensitivity specific to the stimulus modality (e.g., Poulton, 1967). The exponent of this log-log function has, however, been shown to vary with different experimental preparations (e.g., Poulton, 1968). Early investigations of these changes in perceived judgments suggested that subjective judgments of stimulus magnitude could be altered with changes in the array of stimuli presented during the scaling task (e.g., Helson, 1947; Poulton, 1967; Poulton, 1968; Stevens, 1971).

According to one early theory, Adaptation Level Theory (Helson, 1947), in a magnitude-scaling task, participants develop a frame of reference or adaptation level based on the stimuli presented in the task. Participants' judgments of the stimuli are based on the difference between the presented stimulus and the adaptation level. The adaptation level is a weighted logarithmic mean of all the stimuli presented. Changes in the weighted mean of the stimulus distribution that arise from changes in the number, frequency or range of presented stimuli, would result in changes in participants judgments of stimulus values. For example, Helson (1947) reported upward shifts in the point of subjective equality (PSE) when an additional larger stimulus was added to a stimulus set, whereas the PSE was shifted downward when the added stimulus was smaller. Adaptation level theory has also been applied to explanations for shifts in stimulus generalization functions obtained when test stimuli values are varied (e.g., Hansen, Tomie, Thomas & Thomas, 1974; Helson & Avant, 1967). Helson and Avant (1967) showed that stimulus generalization gradients peaked at values close to the center of the test stimulus distribution, not at the standard stimulus value. Hansen et al. (1974) showed that stimulus generalization gradients flattened as the range of test stimuli increased.

Findings of range effects are fairly common in psychophysical scaling studies of many different sensory systems (e.g., Stevens, 1971). Typically, larger stimulus ranges are associated with flatter log-log functions (e.g., DeCarlo, 2005). The present mixing manipulation may be viewed as a range manipulation in which range was varied at values of “none” in the single duration condition, and “some” in the mixed duration condition. Consistent with this range analysis, in the present study, the function for the condition with the larger stimulus range was flatter than the function obtained for the smaller stimulus range. Additionally, in the present study sample stimulus range differed between Experiments 1 and 2. Although a direct comparison between Experiments 1 and 2 cannot be made, the finding that significant differences in slopes between the single and mixed conditions were obtained in Experiment 2, but not in Experiment 1 might be due to the smaller difference in range between the single and mixed conditions (12 to 24 s) in Experiment 1 as compared to Experiment 2 (6 to 24 s).

The locus of this effect of range has been discussed in the perceptual literature (e.g., Algom & Marks, 1990; Mori, 1998; Petzold & Haubensak, 2004; Stewart & Brown, 2004; Stewart, Brown & Chater, 2005). Algom and Marks (1990) discussed the possibility that stimulus range influences the perceptual process as well as response process. One variable that has been discussed as an influence on subjective judgments is the sequence of stimulus presentation, which has been called “sequential dependencies.” Correlations between previously presented stimuli and judgments of a current stimulus have been reported for categorization of tones (Stewart & Brown, 2004), categorization of size (Petzold & Haubensak, 2004), as well as absolute identification of tones (Stewart, Brown, Charter, 2005) and luminescence (Mori, 1998). Although the present study was not designed to investigate these interpretations, post hoc analyses of temporal judgments as a function of the previous sample interval (e.g., 12 s preceded by 12 s, or preceded by 24 s) did not reveal any significant differences of temporal judgments as a function of previous interval. Nevertheless, it might be profitable to simplify the present design so that a more systematic analysis of sequential dependencies would be possible. .

In conclusion, the present study has identified a source of influence on timing performance, the sequence of duration presentation. That is, timing performance differs when a single duration is presented as compared to presentation of mixed sample duration values. Under mixed sample duration value conditions, temporal judgments of the longest sample duration are shorter as compared to single sample duration conditions. Although the shortening associated with mixed sample presentation is similar to the shortening associated with dual tasks, findings for measures of variability are not consistent with this interpretation of the mixed sample duration effect. Measures of variability were smaller under the mixed duration condition relative to the single duration condition. Therefore, the mixed sample duration effect does not appear to be functionally the same as a dual task effect. Furthermore, mixing sample durations appears to have influenced sensitivity to duration. Log-log functions for the mixed duration condition were flatter than those obtained for the single duration condition. Flattening of the log-log function has also been observed in dual task manipulations, such that functions are flatter in conditions with dual tasks relative to single task (timing only) conditions (Brown et al., 1992; Hemmes et al., 2004). In the present study, the locus of the mixing effect on sensitivity is not clear. Lastly, the finding of a larger difference in temporal judgments between the single and multiple sample duration conditions in Experiment 2, suggests that the influence of multiple sample duration values may be enhanced with either an increased range or number of sample duration values.

Table 1

*Order of Conditions for Participants in the Four Experimental Sessions in Experiment 1*

| Group | Session 1 | Session 2 | Session 3 | Session 4 |
|---|---|---|---|---|
| Single First | 12 s Single | 24 s Single | Mixed | Mixed |
| | 24 s Single | 12 s Single | Mixed | Mixed |
| Mixed First | Mixed | Mixed | 12 s Single | 24 s Single |
| | Mixed | Mixed | 24 s Single | 12 s Single |

Table 2

*Mean Coefficients of Variation Under Both Conditions at Each Duration*

| Condition | 12-s Sample Duration | 24-s Sample Duration |
|---|---|---|
| Single Duration | .2436 | .2209 |
| Mixed Duration | .2712 | .2207 |

Table 3

*Mean Proportion Scores Under Both Conditions at Each Duration*

| Condition | 12-s Sample Duration | 24-s Sample Duration |
|---|---|---|
| Single Duration | .8729 | .6838 |
| Mixed Duration | .8791 | .6384 |

Table 4

*Order of Conditions for Participants in the Six Experimental Sessions in Experiment 2*

| Group | Session 1 | Session 2 | Session 3 | Session 4 | Session 5 | Session 6 |
|---|---|---|---|---|---|---|
| Single First | 6 s | 12 s | 24 s | Mixed | Mixed | Mixed |
| | 12 s | 24 s | 6 s | Mixed | Mixed | Mixed |
| | 24 s | 6 s | 12 s | Mixed | Mixed | Mixed |
| Mixed First | Mixed | Mixed | Mixed | 6 s | 12 s | 24 s |
| | Mixed | Mixed | Mixed | 12 s | 24 s | 6 s |
| | Mixed | Mixed | Mixed | 24 s | 6 s | 12 s |

Table 5

*Mean Coefficients of Variation Under Both Conditions at Each Sample Duration*

| Condition | 6-s Duration | 12-s Duration | 24-s Duration |
|---|---|---|---|
| Single Duration | .2518 | .2320 | .2410 |
| Mixed Duration | .2649 | .2569 | .2577 |

Table 6

*T-statistics and p Values Under Each Condition At Each Sample Duration.*

| Condition | 6-s Duration | 12-s Duration | 24-s Duration |
|---|---|---|---|
| Single Condition | 2.26, p< .03 | 4.36, p< .0001 | 7.39, p <0001 |
| Mixed Condition | 2.78, p< .009 | 5.79, p< .0001 | 11.21, p<.0001 |

*Note*: all tests were conducted with 35 degrees of freedom

Table 7

*Mean Proportion Scores Under Both Conditions at Each Sample Duration*

| Condition | 6-s Duration | 12-s Duration | 24-s Duration |
|---|---|---|---|
| Single Duration | .89 | .81 | .67 |
| Mixed Duration | .88 | .76 | .60 |

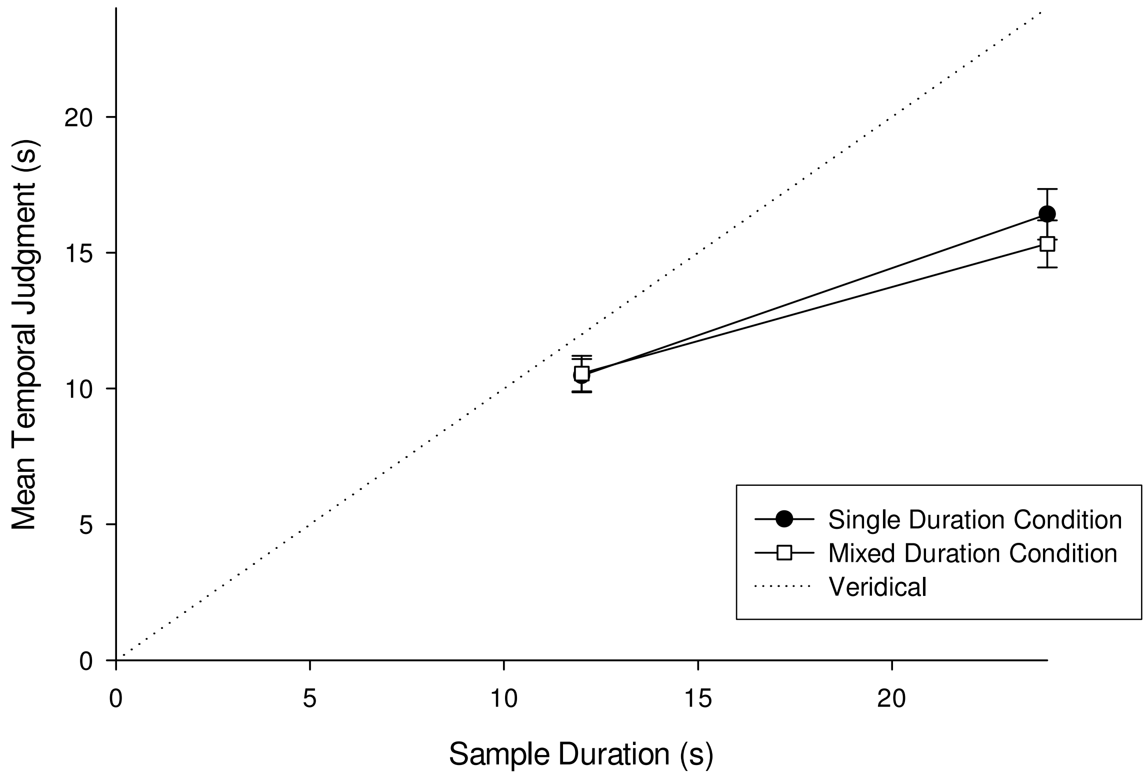

*Figure 1.* Mean temporal judgments for each condition as a function of sample duration.

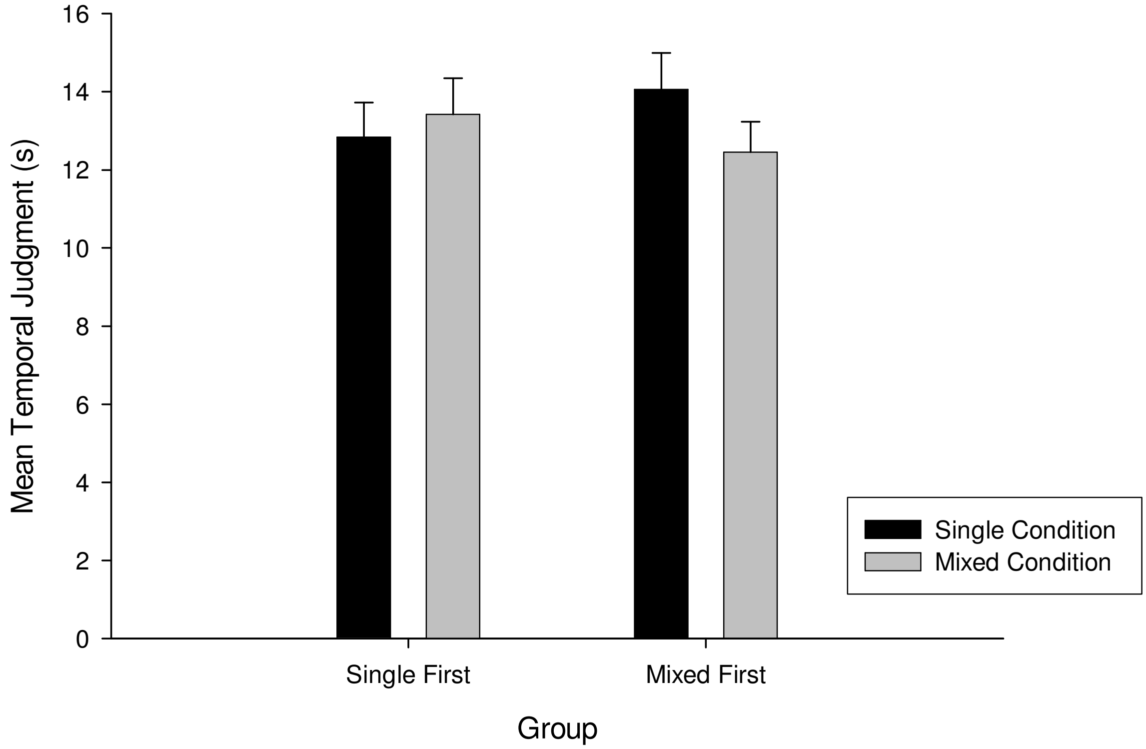

*Figure 2.* Mean temporal judgment for the Single First and Mixed First Groups under both the single first and mixed first conditions.

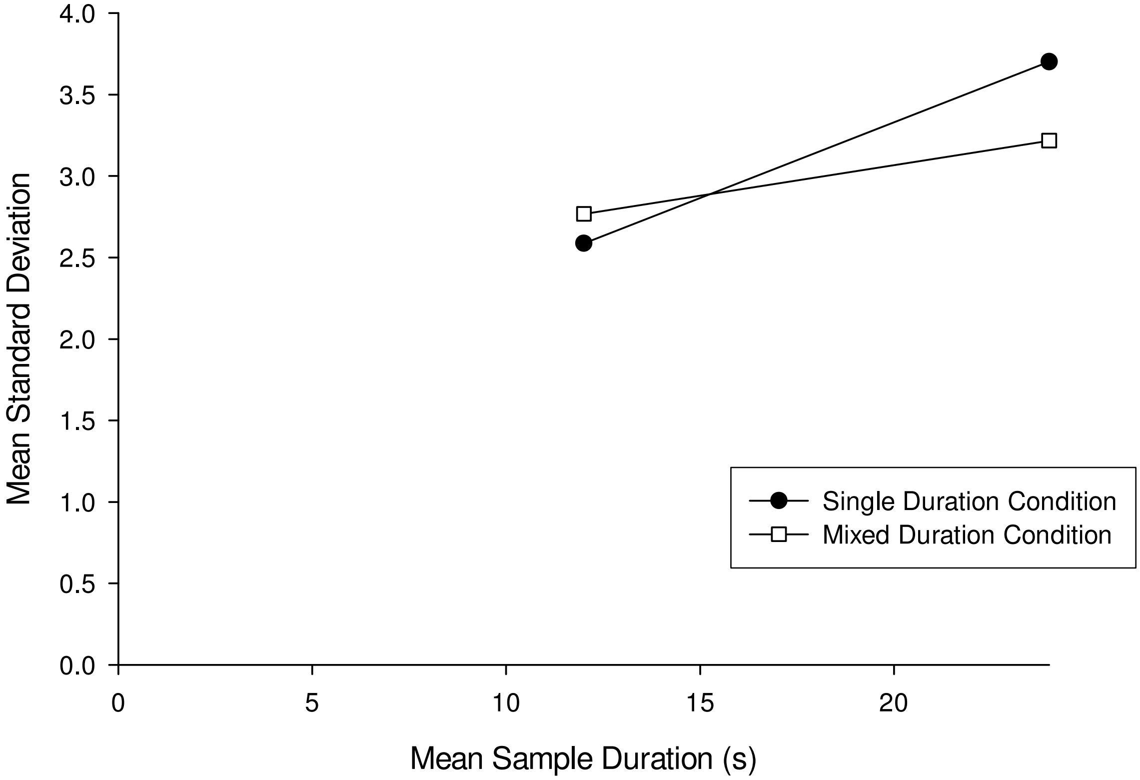

*Figure 3.* Mean standard deviations for each condition as a function of sample duration.

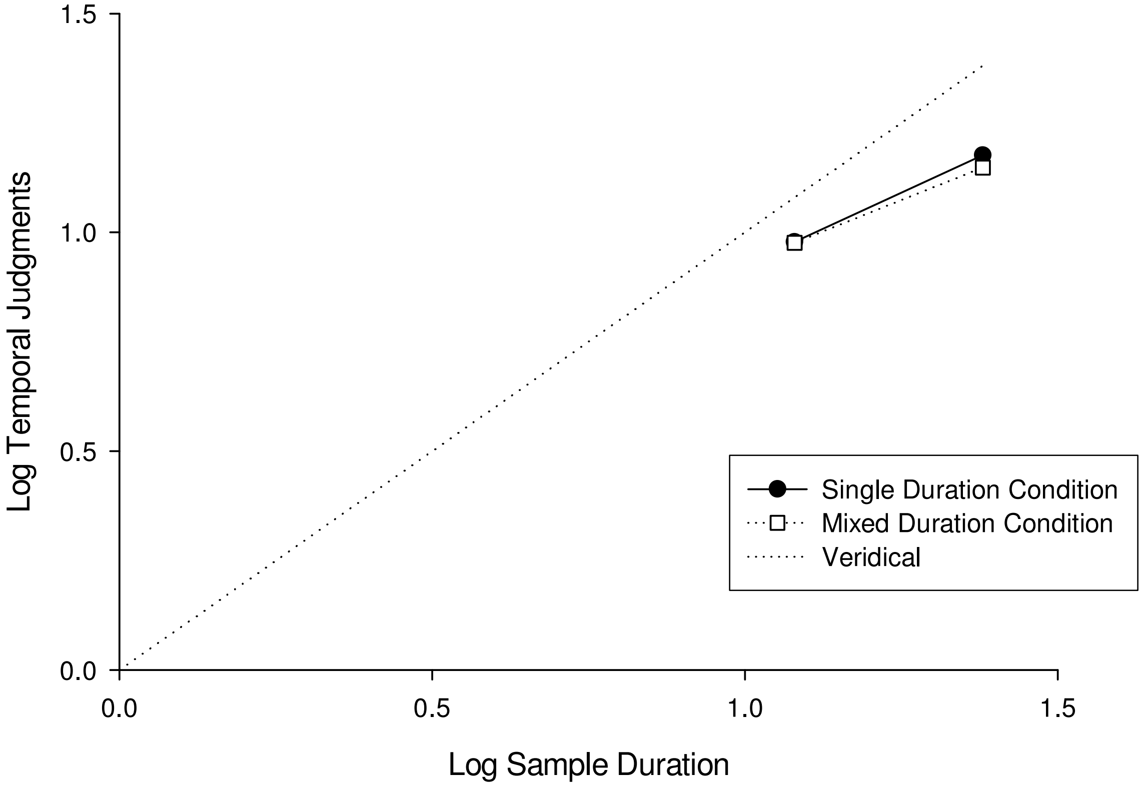

*Figure 4.* Mean log temporal judgments for each condition as a function of log sample duration.

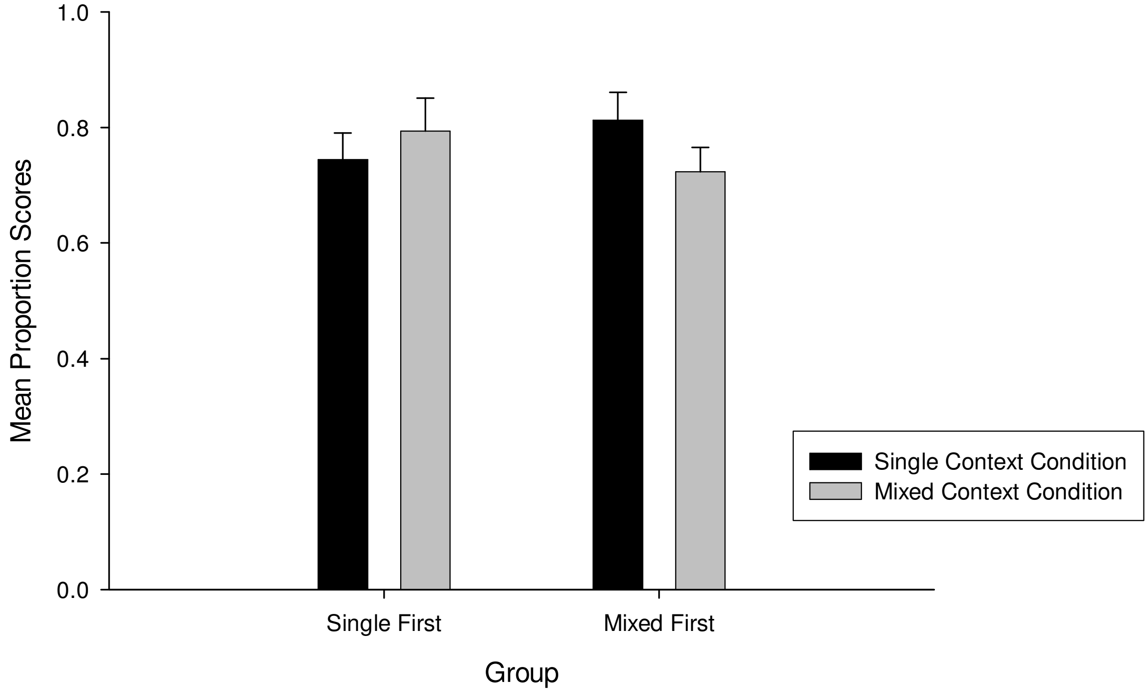

*Figure 5.* Mean proportion scores for the Single First and Mixed First Groups under both the single and mixed conditions.

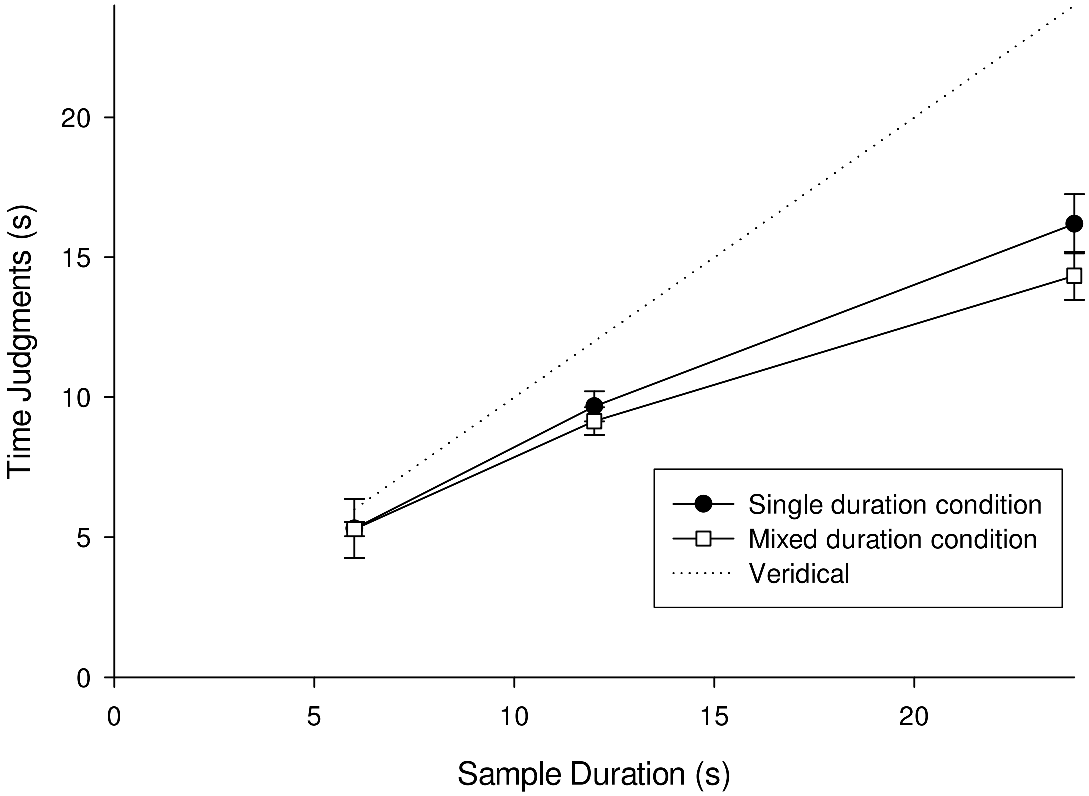

*Figure 6.* Mean temporal judgments for the single and mixed duration conditions as a function of sample duration.

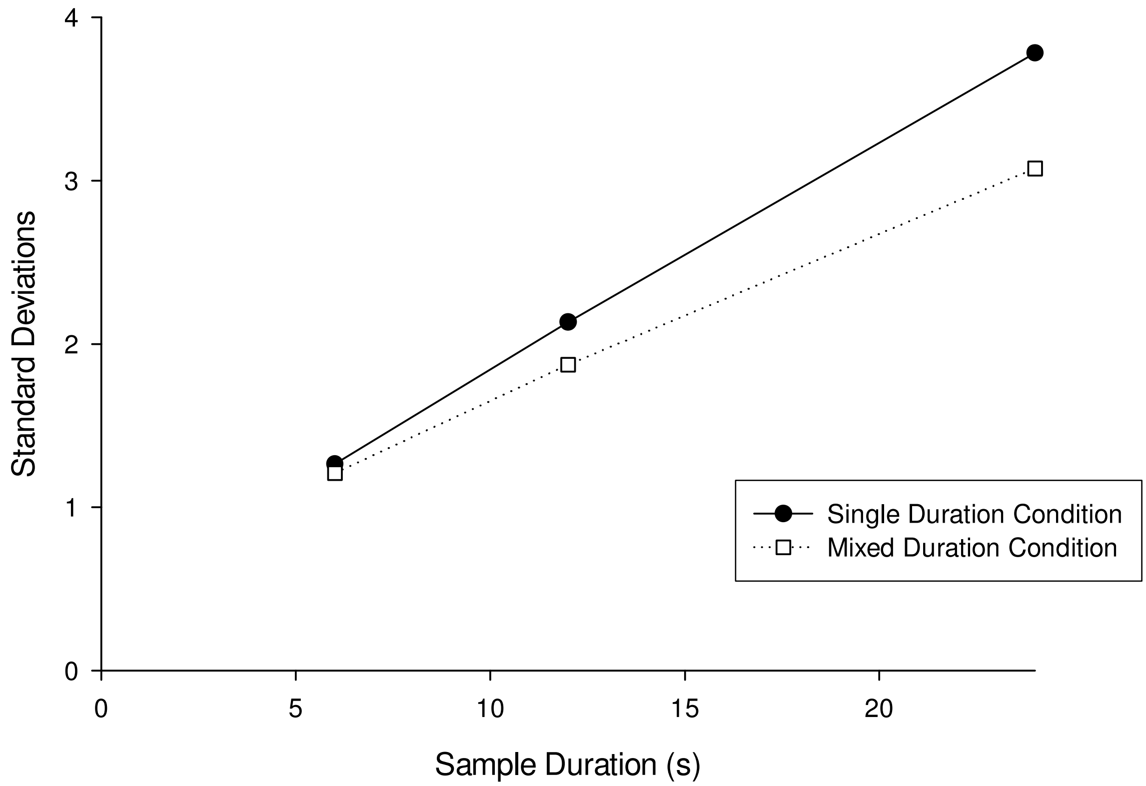

*Figure 7.* Mean standard deviations for the single and mixed duration conditions as a function of sample duration.

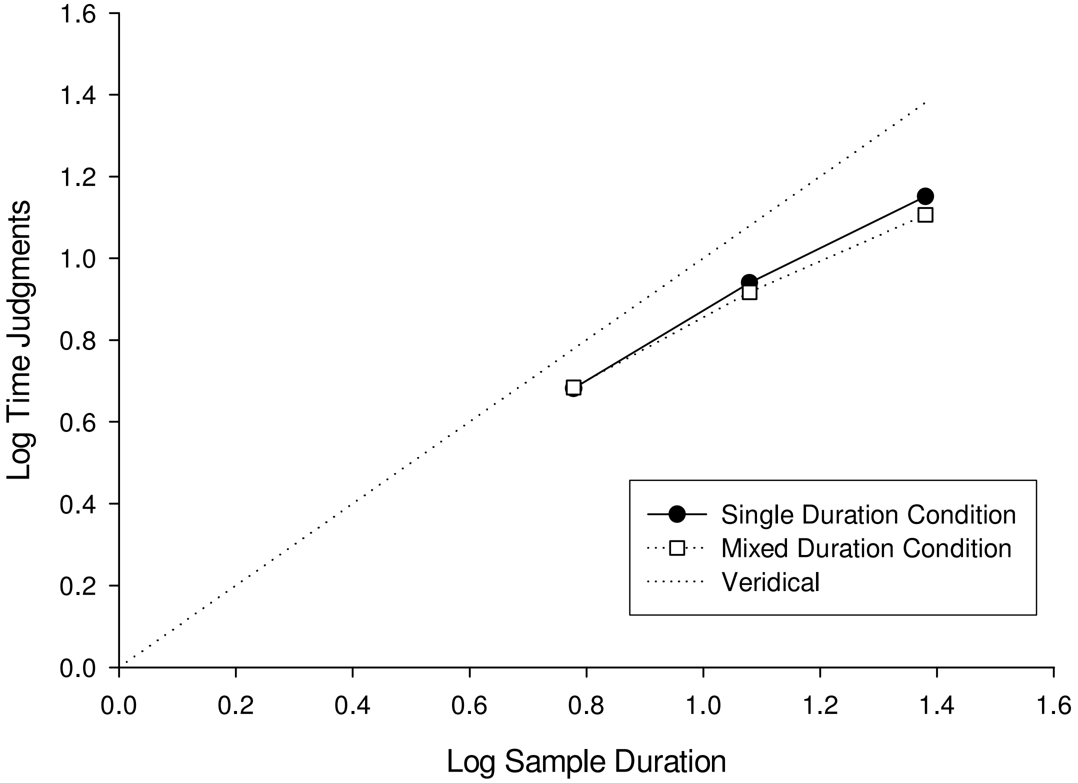

*Figure 8.* Mean log temporal judgment as a function of log sample duration for both the single and mixed duration conditions.

# Appendix A

## INSTRUCTIONS FOR TEST SESSIONS

On each trial you will be presented with a GREEN SQUARE at the center of the screen for a specific amount of time that we will call the TARGET TIME. When that GREEN SQUARE disappears, a PURPLE SQUARE will appear in the same location and will remain visible until you click the left key on the mouse. Your task is to click the mouse key when you estimate that the PURPLE SQUARE has been on as long as the GREEN SQUARE. That is, you are to estimate the TIME OF THE GREEN SQUARE and leave the PURPLE SQUARE on for the same amount of time.

----------STOP AT THIS POINT AND CALL THE EXPERIMENTER----------

----------REPEAT INSTRUCTIONS TO EXPERIMENTER---------

On all trials, numbers will flash at the center of the GREEN SQUARE. You should read aloud each number when it appears, pronouncing each place name. For example, if you see the number 135, you should say 'one hundred thirty five' not 'one thirty five'. Your voice will be recorded during the session.

For practice, read aloud the following numbers:

5923 310 1408

Remember that your task is to terminate the PURPLE SQUARE WHEN YOU ESTIMATE THAT IT HAS BEEN ON AS LONG as the GREEN square.

----------STOP AT THIS POINT AND CALL THE EXPERIMENTER----------

----------REPEAT INSTRUCTIONS TO EXPERIMENTER----------

Remember to pronounce aloud as many numbers as you can whenever you see them.

REMEMBER TO LEAVE THE PURPLE SQUARE ON AS LONG AS THE GREEN SQUARE. PLEASE, DO YOUR BEST!!

DO YOU HAVE ANY QUESTIONS???

If you don't, make sure the mouse is in front of you and....

Table A1

*Analysis of Variance for Temporal Judgments*

| Source | *df* | *F* | *p* |
|---|---|---|---|
| | Between Subjects | | |
| Group | 1 | .01 | .9299 |
| | Within Subjects | | |
| Duration | 1 | 187.41** | <.0001 |
| Duration x Group | 1 | 1.25 | .2702 |
| Condition | 1 | 1.24 | .2719 |
| Condition X Group | 1 | 5.77** | .0213 |
| Condition X Duration | 1 | 5.78** | .0212 |
| Condition X Duration X Group | 1 | .02 | .8937 |

*Note.* Asterisks denote significant effects at the *p* value specified in the table.

Table A2

*Analysis of Variance for Standard Deviations for All Four Experimental Sessions*

| Source | *df* | *F* | *p* |
|---|---|---|---|
| | Between Subjects | | |
| Group | 1 | .01 | .9181 |
| | Within Subjects | | |
| Duration | 1 | 19.02** | <.0001 |
| Duration x Group | 1 | .31 | .5790 |
| Condition | 1 | .49 | .4894 |
| Condition X Group | 1 | 2.28 | .1392 |
| Condition X Duration | 1 | 7.42** | .0097 |
| Condition X Duration X Group | 1 | 1.14 | .2933 |

*Note.* Asterisks denote significant effects at the *p* value specified in the table.

Table A 3

*Analysis of Variance for Coefficients of Variation Scores (CV) for All Four Sessions*

| Source | *df* | *F* | *p* |
|---|---|---|---|
| | Between Subjects | | |
| Group | 1 | .04 | .8386 |
| | Within Subjects | | |
| Duration | 1 | 8.06** | <.0072 |
| Duration x Group | 1 | .28 | .5999 |
| Condition | 1 | 1.31 | .2600 |
| Condition X Group | 1 | .00 | .9769 |
| Condition X Duration | 1 | 3.04 | .0895 |
| Condition X Duration X Group | 1 | .16 | .6900 |

*Note.* Asterisks denote significant effects at the *p* value specified in the table.

Table A 4

*Analysis of Variance for Log Time Judgments for All Four Sessions*

| Source | *df* | *F* | *p* |
|---|---|---|---|
| | Between Subjects | | |
| Group | 1 | .02 | .8799 |
| | Within Subjects | | |
| Duration | 1 | 302.62** | <.0001 |
| Duration x Group | 1 | 2.49 | .1232 |
| Condition | 1 | 1.26 | .2678 |
| Condition X Group | 1 | 6.82** | .0128 |
| Condition X Duration | 1 | 3.31 | .0768 |
| Condition X Duration X Group | 1 | 2.03 | .1626 |

*Note*. Asterisks denote significant effects at the *p* value specified in the table

Table A5

*Analysis of Variance for Proportion Scores*

| Source | *df* | *F* | *p* |
|---|---|---|---|
| | Between Subjects | | |
| Group | 1 | .00 | .9887 |
| | Within Subjects | | |
| Duration | 1 | 93.87** | <.0001 |
| Duration x Group | 1 | 1.23 | .2735 |
| Condition | 1 | .53 | .4721 |
| Condition X Group | 1 | 6.56** | .0145 |
| Condition X Duration | 1 | 3.17 | .0831 |
| Condition X Duration X Group | 1 | 2.92 | .0956 |

*Note.* Asterisks denote significant effects at the *p* value specified in the table.

# Appendix B

Table B1

*Analysis of Variance for Temporal Judgments*

| Source | *df* | *F* | *p* |
|---|---|---|---|
| | Between Subjects | | |
| Group | 1 | .75 | .39 |
| | Within Subjects | | |
| Duration | 2 | 165.37** | <.0001 |
| Duration x Group | 2 | .89 | .42 |
| Condition | 1 | 6.57** | .02 |
| Condition X Group | 1 | 3.74 | .06 |
| Condition X Duration | 2 | 9.13** | .0003 |
| Condition X Duration X Group | 2 | 1.72 | .19 |

*Note.* Asterisks denote significant effects at the *p* value specified in the table.

Table B2

*Analysis of Variance for Standard Deviations*

| Source | *df* | *F* | *p* |
|---|---|---|---|
| | | Between Subjects | |
| Group | 1 | 3.44 | .07 |
| | | Within Subjects | |
| Duration | 2 | 60.88** | <.0001 |
| Duration x Group | 2 | 1.03 | .36 |
| Condition | 1 | 9.92** | .003 |
| Condition X Group | 1 | 5.34** | .03 |
| Condition X Duration | 2 | 5.21** | .008 |
| Condition X Duration X Group | 2 | 1.19 | .31 |

*Note.* Asterisks denote significant effects at the *p* value specified in the table.

Table B3

*Analysis of Variance for Coefficients of Variation (CV)*

| Source | *df* | *F* | *p* |
|---|---|---|---|
| | Between Subjects | | |
| Group | 1 | 2.51 | .12 |
| | Within Subjects | | |
| Duration | 2 | .79 | .46 |
| Duration x Group | 2 | 1.84 | .17 |
| Condition | 1 | 2.77 | .11 |
| Condition X Group | 1 | .11 | .75 |
| Condition X Duration | 2 | .22 | .81 |
| Condition X Duration X Group | 2 | 1.26 | .29 |

*Note.* There were no significant effects.

Table B4

*Analysis of Variance for Log Temporal Judgments*

| Source | *df* | *F* | *p* |
|---|---|---|---|
| | | Between Subjects | |
| Group | 1 | .07 | .79 |
| | | Within Subjects | |
| Duration | 2 | 399.15** | <.0001 |
| Duration x Group | 2 | .45 | .64 |
| Condition | 1 | 1.78 | .19 |
| Condition X Group | 1 | .61 | .44 |
| Condition X Duration | 21 | 3.54** | .04 |
| Condition X Duration X Group | 21 | .22 | .81 |

*Note.* Asterisks denote significant effects at the *p* value specified in the table.

Table B4

*Analysis of Variance for Proportion Scores*

| Source | *df* | *F* | *p* |
|---|---|---|---|
| | | Between Subjects | |
| Group | 1 | .57 | .46 |
| | | Within Subjects | |
| Duration | 2 | 58.52** | <.0001 |
| Duration x Group | 2 | .82 | .45 |
| Condition | 1 | 3.01 | .09 |
| Condition X Group | 1 | 3.06 | .09 |
| Condition X Duration | 2 | 3.04** | .0545 |
| Condition X Duration X Group | 2 | .04 | .96 |

*Note.* Asterisks denote significant effects at the *p* value specified in the table.

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